VISUAL TIME

by

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Abstract

Perception of time is an understudied topic, unlike the perception of space, for instance, where mechanisms are understood at multiple levels. Big open questions remain: what is the nature of the representations that are used to process time? How do we experience time? Does time seem to slow down or speed up in certain experiences? How does the content of our visual experience affect remembered duration? These questions have been either largely evaded or understudied in the literature on time perception. In this dissertation, I attempt to address basic questions on the content and experience of time perception. Chapter 01 introduces the reader to puzzling questions on the perception and experience of time, and it lays the outline for the dissertation. In Chapter 02, I discuss the literature on temporal order (knowing which of the two things in our experience happened first / second) and simultaneity judgments (knowing if the two things in our experience happened simultaneously.) These two processes are believed to be crucial for time perception. I will discuss the existing literature in order to speculate on what it could imply for the contents and formats of temporal representation. In chapter 03, I will focus on how we experience a moment in our visual experience. Specifically, I investigate whether events that are happening across the visual field at a given time are experienced as such. I will provide empirical support for this investigation by developing a novel behavioral task involving Rapid Serial Visual Presentation (aka RSVP) task. The results suggest that a moment in our visual experience stitches together events that happened at different times across the visual field. Chapter 04 will focus on how we obtain a sense of elapsed duration. Specifically, I

will investigate what it means when we feel like ‘time has slowed down. Here I develop another novel behavioral task that allows me to contrast memory for duration and the perception of ongoing duration. The results indicate that our experience of time does not really slow down, but it can be distorted in immediate memory. Finally, Chapter 05 will investigate the underlying mechanisms responsible for distortions of duration judgments in our memory and it will set an agenda for future directions.

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2 Cool cool cool!

3 For blessing us with his dog-ness.

4 For being extremely organized about everything in life

5 For all the music, road trips and the food in our lives

6 For having been there, done that!

7 For spectacularly screwing up some things in your life, and then some chill. But mostly chill.

8 Some of my best memories of Baltimore are in NYC

9 For existing

10 For radiating awesomeness at 31 kilo chills per second

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Introduction

Time is precious. It is not like other precious things though. We cannot hold time in our hands like a precious necklace. Nor is it like money – which can either flourish or perish depending on how we use it. Time is an abstract quantity that requires a mind to appreciate, and it has existed before we could measure it. Among the things that makes studying perception of time interesting is the flow of time. Specifically, what is the present that we experience? What does it contain? Is my experience of the present the same as yours? And how does it transition into the past?

William James (James, Burkhardt, Bowers, & Skrupskelis, 1890) once described the present as follows: “The practically cognized present is no knife-edge, but a saddle-back, with a certain breadth of its own on which we sit perched, and from which we look into two directions into time. The unit of composition of our perception of time is a *duration*, with a bow and a stern, as it were -- a rearward -- and a forward looking end.”

Relatively little is known, however, about how we come to experience and perceive the present and the flow of time. Specifically, what constitutes a unit of experience in time? How long is it? How is it represented in our mind? This dissertation is my attempt to understanding the underlying mechanisms involved in time perception. Through this dissertation I will theorize, investigate and develop novel formal approaches to understand how we represent, experience and remember the perceived present.

The outline of this dissertation is as follows: In Chapter 02, I will spend a great deal of ‘time’ (lol; pun intended) on the perception of order and simultaneity in time. Temporal order and simultaneity are considered as the building blocks of our experience in time. I will present three different kinds of representations that could be used to support the perception of temporal order. Additionally, I will review the existing literature with an eye on these three kinds of representations and explain various findings about the perception of order and simultaneity.

In Chapter 03, I will focus on a moment in our visual experience. Specifically, I will investigate whether a moment of visual experience reflects a moment in the actual real world. I will support this investigation using a novel psychological paradigm that is a variant of the Rapid Serial Visual Presentation (aka RSVP) task. The results from this investigation suggest that a moment of our visual experience stitches together events that happened at different times across the space in the real world.

Chapter 04 then explores the experience of elapsed duration. Specifically, do we experience time as slowing down in some situations? I will investigate this question using another novel psychological paradigm that allows me to compare the ongoing experience of duration with how it is remembered. The results from this investigation suggest that our experience of time is more or less the same for atypical events. Instead, the way we remember such experiences is distorted.

Chapter 05 further probes into the mechanisms responsible for distorting how we remember events. Here I will identify three questions that are intended to identify three potentially fruitful paths and open questions for future research.

2

A Tutorial Review on Temporal Properties in Visual Perception

The purpose of this review is to examine the nature of temporal properties in visual processing. The discussion is predicated on a key distinction: the difference between having an ability to report temporal properties and having percepts that themselves *represent* those properties. In particular, we seek to understand whether perception *represents* temporal properties, as opposed to representing non-temporal properties from which post-perceptual representations of temporal properties can be derived. We outline the distinction between the two scenarios in the paragraph below

2.1 In what ways *could* temporal properties be represented?

When we experience time, do we readily have a representation available for it in our perception (just like we do for brightness or shape)? Or perhaps we rely on some other form of non-temporal representation that could be used to infer time? The existing literature has mostly evaded questions about the nature of the representations that produce a perception of time. Two important distinctions, in particular, have been conflated: (1) between a representation of temporal properties and a representation that has temporal properties. The numerals of elapsed time at the bottom of a YouTube video are an example of a representation of a temporal property. The video itself has temporal properties in the sense that it unfolds over a fixed duration. (2) The second important distinction is between a representation of temporal properties and a representation of other properties that are consulted when questions about time arise. Starting, stopping, and then consulting a stopwatch to judge the duration of an event is an example of using a representation of time as the source for knowledge of time. Inferring that a cup of coffee has been sitting out for more than half an hour on the basis that it is cold is an example of making an inference about duration from other properties known to depend on duration.

2.1.1 Three kinds of representations

What kinds of representations might the human mind use to produce knowledge about duration? There are ***three broad categories*** of representational formats and contents that *could* provide cognition with information about time. The ***first*** kind of representation would be the one that is both about temporal properties (contents) and that uses temporal properties as the vehicle for the representation (the format). For example, suppose we have a wall clock to measure time. It takes about one entire minute for the seconds hand to make one complete circle. The wall clock is intended to represent time (content), and it uses time as a part of its representation, i.e., it actually takes one entire rotation of the seconds hand to indicate a minute. Therefore, the wall clock represents time by directly resembling the duration represented. Another simple example is where we can represent the duration of a stimulus on screen by pressing and holding down a button. Note that both these cases are using time to represent time. This form of representation is purely perceptual in the sense every moment that is represented by this kind is part of our experience. Some form of a neural accumulator and or gating mechanism dedicated to representing time is an example of this kind of representation that has been suggested for, but not yet identified in the brain.

The ***second*** kind of representation would be about time, but it does not use time. For example, if you know that it takes you 20 minutes to walk a mile, on average, then you can let your friends know that you will meet them 2 miles away in about 40 minutes. In this example you are using the representation of 2 miles to represent 40 minutes duration. In doing so, we are not using any clock like representations, but a mere correspondence between the distance travelled and the time it took. Here you rely on representations that are about time, but do not use time. The representation used here is about distance which is used to convey time. This form of representation is symbolic.

The ***third*** kind of representation would be the one that is not about time, and it does not use time, but it can be consulted to license an inference when a question about time arises. For example, consider the apparent motion illusion. The fast and simultaneous disappearance of an object in location A and reappearance in location B gives rise to the percept of object motion from A to B as long as the two locations are close. This can be implemented in the brain using the Reichardt motion detector circuit. Now suppose we presented two discs to you asynchronously, and we asked you to report which disc came first. You could measure the time of appearance of each disc using a stopwatch, and then report the disc with the earlier time. Alternatively, you could use the motion information from the Reichardt detector to infer which disc came earlier. Note that in the latter scenario, the representations are about motion, and not about time. But they can be consulted to infer temporal properties such as order - i.e., which of the discs appeared first - and simultaneity - whether they both appeared together. This form of representation can be perceptual, but it is not about the perception of time.

Each of the three representational kinds has its advantages / limitations. For example, the ***second*** type of representation is a representation that is informed by post-perceptual cognition, and it could be biased. For example, in the walking scenario described above, if you misremembered how long it took you to walk a mile you would end up giving a wrong estimate to your friends. In this scenario, the representation in your memory biased your estimate of how long it took. Similarly, given that the Reichardt detector's primary purpose is not to compute time, the ***third*** type of representation can be biased as well. For example, the detector might be more accurate in sensing motion in one direction, and not so great in other directions. The detector is biased towards horizontal motion in this scenario. Thus, inferring temporal properties from this detector would result in a biased inference. On the other hand, having an hourglass like representation might be more accurate for producing knowledge about time. However, it might be computationally costly to represent every moment in time. An hourglass like representational kind would also emphasize that we have a dedicated system for processing time that does not rely on other perceptual representations.

2.2 Representation of temporal properties from the perspective of Temporal Order and Simultaneity

Several temporal properties of vision have been studied extensively in the literature, but it is not always obvious what kinds of representations they imply. In fact, it is not at all clear that representational formats can be inferred from the existing experiments. We therefore review the literature here with an eye towards determining what it can say about the temporal contents of representations in experiments investigating the cognitive psychology of time perception. The focus will be on two key temporal properties: 1) order, and 2) simultaneity - since they form the building blocks of time perception. (Chapter 04 will focus explicitly on duration, so we reserve discussion of the literature until then.) A secondary but related set of questions about these properties pertains to whether they are dissociable, that is are they independent, or actually inferred from the same core. The nature of this distinction will become clearer as the discussion proceeds.

2.2.1 Methodological introduction to the two paradigms

Temporal properties such as order and simultaneity are crucial for understanding how we process time. In vision and other modalities they have largely been studied using two types of paradigms: 1) Temporal Order Judgments 2) Simultaneity Judgments. Typically, in these paradigms stimulus pairs are presented to the observer at varying times - i.e., Stimulus Onset Asynchronies (SOA) (see Figure 1). The stimulus pairs could either be from the same modality (e.g., vision), or different modalities (e.g., vision and touch). Participants are either required to report if they perceived the stimulus pair as simultaneous (Simultaneity Judgments, or SJ), or the order in which they perceived them (Temporal Order Judgments, or TOJ).

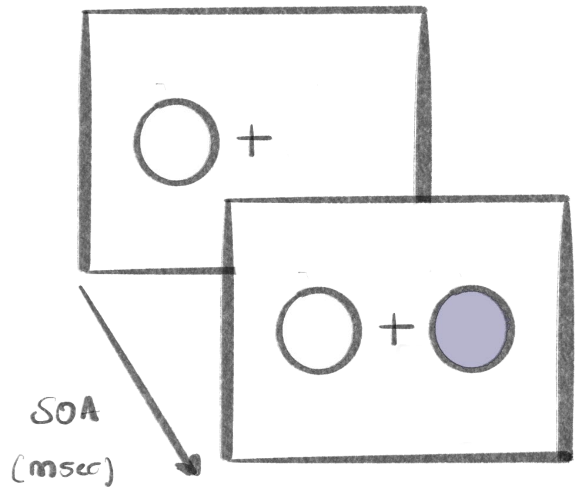

Figure 1 : Illustration of temporal order and simultaneity tasks

Participants are presented with two stimuli from the same, or different modality. The two stimuli appear at varying onsets (typically in milliseconds), and they are instructed to report either the order in which they perceived them (Temporal Order task), or whether they perceived them as having appeared simultaneously (Simultaneity Judgment task).

The responses are quantified at various SOAs in terms of the probability of having perceived stimulus 1 first (for the Temporal Order Judgment task), or the probability of having perceived both the stimuli simultaneously (for the Simultaneity Judgment task).

2.2.2 Metrics used in analyzing the data in the two paradigms

The probability reports for the Simultaneity Judgment (SJ) task can be modelled as a Gaussian distribution. That is, the frequency of responses peaks at a particular Stimulus Onset Asynchrony (SOA), and they fall off as this metric is varied. The SOA at which the distribution peaks is defined as the **Point of Subjective Simultaneity** (**PSS**). This is the point at which participants are highly likely to report the two stimuli as having been perceived simultaneously. The **width** of the distribution (the standard deviation) is thought to be related to the **Temporal Integration Window (TIW)** as shown in Figure 2.

The Temporal Integration Window refers to the range of SOAs in which participants most likely report the stimulus pair to be simultaneous. For example, having a temporal integration window of 45 msec would imply that we are likely to report the stimuli as simultaneous even if one stimulus trails / leads the other by 22.5 msec.

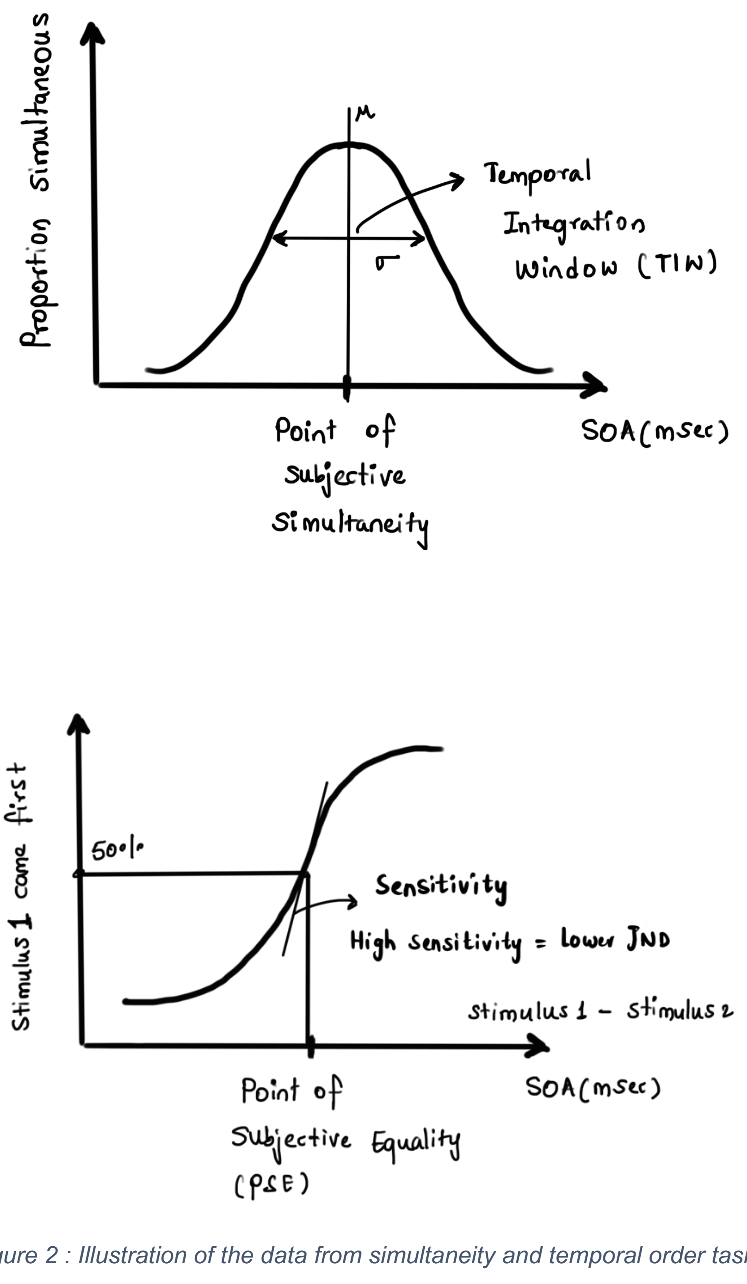

Figure 2 : Illustration of the data from simultaneity and temporal order tasks

Temporal order judgments on the other hand reflect the probability with which participants report one stimulus to have occurred first with varying SOA. That is, participant reports often pick one stimulus to have appeared 1st for a range of SOAs, and switch to the other stimulus as the SOAs increase. They are described psychometrically using S-shaped cumulative Gaussian distributions. Two parameters of interest from these distributions are the 50% probability response point (**Point of Subjective Equality - PSE**), and the slope of the curve. The PSE is defined as the onset asynchrony at which participants' reports are at chance level, i.e., participants report both the stimuli as having appeared first with equal probability. **Point of Subjective Equality (TOJ)** and **Point of Subjective Simultaneity (SJ)** have often been used interchangeably in the literature. However, we will treat them as two separate definitions in the scope of this review. The reason for this distinction will get clearer when we discuss whether the temporal order and simultaneity judgments stem from the same mechanism or not. But for now PSE here refers to the asynchrony at which participant reports are at chance level. Further, the slope of the curve at PSE reflects participants' sensitivity to SOA, and is often described in terms of **Just Noticeable Difference (JND)**. JND in this context is defined as the minimum amount of the onset asynchrony needed to be changed in order for the participant to notice the order. Lower JND values imply higher sensitivity to discriminate between the order in which two stimuli were presented, and vice-versa.

2.2.3. What do the two tasks tell us about the nature of representations of time?

The core idea behind the psychophysics of temporal order and simultaneity judgments is to investigate the nature of our temporal experience - specifically how do we experience events as happening simultaneously and how do we perceive ordered events? Simultaneity and order are two crucial components of temporal processing since they form the building blocks for perceiving higher order constructs of temporal experiences such as duration, causality etc. For example, in determining the elapsed time of an experienced event, it is crucial to know the starting and ending of the event. Further, that the end point is a distinct marker from the start point, and is in succession to the start point. Alternatively, we could also determine the duration by forming associations with symbols. For example, we could say that the earth takes 365 days to complete one revolution around the sun by merely reading about it in a book. Here we are not using any start and end markers to determine the duration of this revolution. Although notice that this kind of deduction does not reflect our experience of the elapsed time. A similar case can be made against perception of causality without perceiving order and simultaneity. Therefore, studying the perception of order and simultaneity is crucial for studying the experience of perceived time.

However, the nature of the representations that produce a sense of order and simultaneity is not clearly understood. Specifically, do we have an clock-like machinery that represents every moment to infer when two things are simultaneous, or the order in which they appeared? If so, how is this reflected in the judgment tasks? Or do we infer these properties using strictly non-temporal representations (like in the examples of walking, and apparent motion as described above)? And how is this reflected in the judgment tasks of simultaneity, and temporal order? Several behavioral and cognitive factors about temporal order and simultaneity judgments confound our deductions about the nature of the representations. Some of these have to do with multi-modal processing of stimuli, age related differences, task specific factors, and cognitive biases amongst many others. We will go over these in detail in the sections below and try to speculate about the nature of representations of temporal processing while unconfounding the factors that affect them.

2.3 General findings about Temporal Order & Simultaneity

Perception of temporal order and simultaneity across senses is subject to sensory processing differences. The neural processing speed for vision is slower compared to audition. In addition, for the same given distance light reaches our retina much faster than sound reaches the cochlea. Given that the neural processing and sensory stimulation for vision and audition happen at different speeds, it is intuitive to think that we do not report a pair of audio and video stimuli in their correct order all the time. In fact, the PSEs and PSSs measured in TOJ and SJ respectively have been shown to shift toward the video-led stimulus (Zampini, Brown, et al., 2005; Zampini, Guest, Shore, & Spence, 2005; Zampini, Shore, & Spence, 2003). For example, in their study on audio-visual simultaneity, Zampini and colleagues (Zampini et al., 2003) manipulated the SOA between audio and visual stimuli across three different experiments, using the method of constant stimuli, and staircase methods while manipulating the location of the visual stimuli. Their results suggest that SOAs of the range 19.4 - 167 msec (subject to the experiment design) are required for participants to report the two stimuli as simultaneous. Specifically, they found that a simultaneously presented auditory stimulus is reported to have appeared first. In other words, a video stimulus has to lead the auditory stimulus in order to report it as appearing simultaneously.

Similarly, neural processing speed for tactile stimuli is much slower compared to both visual and auditory processing. Zampini and colleagues (Zampini, Brown, et al., 2005) have examined TOJs with audio-tactile stimuli and have shown that the PSE for audio-tactile stimuli is around 80 msec. This means that when the auditory stimulus leads the tactile stimulus by 80 msec, participants are at chance determining which stimulus occurred first. Thus, differences in processing speeds across the modalities put constraints on the perception of temporal order and simultaneity.

Further, the measured PSEs within a single modality of a Temporal Order Judgment task have also not been recorded at 0 msec SOA under many task conditions (Hirsh, 1959; Rutschmann, 1966; Stelmach & Herdman, 1991). In other words, participants did not report the two visual stimuli as simultaneous even when they objectively appeared simultaneously with 0 sec asynchrony between them. In Chapter 03, I also present evidence that in vision a foveal stimulus must similarly lead an eccentric stimulus for the two to appear as simultaneous. In the experiments involving temporal order within a single modality, two discs were presented on the screen, and participants were asked to judge the order in which they appeared. Cognitive factors such as attention have been shown to influence the perception of temporal order and simultaneity in these experiments. Thus shifting the PSE away from 0 msec even when the stimuli were presented at the same time within the given modality. Additionally, findings in the literature indicate variability in reports across various TOJ and SJ tasks. For example, JNDs measured for audio-visual modalities are between 25-50 msec (Keetels & Vroomen, 2005; Zampini, Guest, et al., 2005), while the measured JNDs for audio-tactile pairs were around 80 msec (Zampini, Brown, et al., 2005), and 35-65 msec for visual-tactile pairs (Keetels & Vroomen, 2008; Spence, Shore, & Klein, 2001). However, an early study by Hirsh and Sherrick Jr (Hirsh & Sherrick Jr, 1961) used well trained participants, and found consistent JNDs of 20 msec across audio-visual-tactile modalities.

What does this variability tell us about the contents of temporal representations? What explains the striking variability in these findings? I discuss the specific factors that influence the processing in these tasks in the paragraphs below.

2.3.1 Factors affecting performance in TOJ and SJ

Spatial separation between the stimuli has been shown to be an influencing factor in temporal order and simultaneity judgments. For example, in their audiovisual simultaneity study, Zampini and colleagues (Zampini, Guest, et al., 2005) manipulated the spatial location of the auditory and visual stimuli in a paradigm while varying the SOA between auditory and visual stimuli. Participants judged whether the two presented stimuli were simultaneous. Across three experiments, they found that participants were more likely to report the two stimuli as simultaneous if they were spatially congruent as opposed to spatially separated. That is, the observed temporal integration windows were wider for the spatially congruent case as opposed to spatially incongruent case.

Spatial separation has also been shown to affect the temporal order judgment task. Zampini and colleagues (Zampini et al., 2003) conducted an audiovisual temporal order judgment task with spatially separated stimuli, and have shown that participants were highly sensitive in reporting the temporal order (in other words, their JNDs were smaller) when the stimuli across the modalities were spatially separated. The JNDs for spatially separated stimuli within each modality did not differ much between auditory and visual modalities.

One possible reason why spatial congruency affects our multi-sensory judgments is because we are used to processing sound and light emanating from a single source as having occurred simultaneously, *aka the unity assumption*. Therefore, spatial congruency of the two stimuli might trick participants into believing that the two stimuli are simultaneous even when the SOA between them is large enough. Similar effects have been documented in the literature (Bertelson & Aschersleben, 2003; Kitagawa, Zampini, & Spence, 2005; Spence & Squire, 2003; Sugita & Suzuki, 2003). Together, these results suggest that spatial location affects the observed responses in multi-sensory temporal judgments.

Stimulus properties can also influence judgments in TOJ and SJ paradigms. Certain stimuli such as flashes and beeps involve sudden changes in energy, and they are easier to perceive. For example, Van der Burg and colleagues (der Burg, Cass, Olivers, Theeuwes, & Alais, 2010) have found in a visual search task, participants were able to look for a visual target more quickly when it is paired with a synchronous auditory cue compared to a no auditory cue condition. Furthermore, in order for this synchrony to aid visual search, abrupt visual events are required, suggesting an advantage for processing abrupt transient stimuli. Processing these stimuli can be facilitated by specific neural mechanisms that could also aid in processing time. For example, consider the scenario where two flashes are presented at different locations in a TOJ paradigm. A feature specific mechanism such as motion detection that is triggered by the SOA between the stimuli could also drive the results of TOJ. This is exactly what

Fink and colleagues (Fink, Ulbrich, Churan, & Wittmann, 2006) found. In their study, they compared TOJs both across and within modalities by presenting participants with either flashes and color changes (visual domain), or clicks and tones (auditory domain). They hypothesized that if judgments are not influenced by stimulus specific mechanisms, then the observed TOJ data should more or less reflect the underlying temporal order processing. Thus, one should expect a strong correlation between the response distributions for flashes and changing color stimuli (and similarly for clicks and tones). However, they did not find significant correlations between the two stimuli pairs (flash vs. color, and click vs. beep). Their results suggest that stimulus dependent mechanisms are influencing TOJs.

Additionally, Van Ejik and colleagues (Van Eijk, Kohlrausch, Juola, & van de Par, 2008) have also explored the role of stimulus type in judging audiovisual temporal order and simultaneity. In their study, participants had to judge temporal order and simultaneity between flash and click pairs, and a bouncing ball and a collision sound. They found that the Point of Subjective Simultaneity (PSS) values obtained from the two stimulus complexities for SJ were consistent for both flash and click events. However, the Point of Subjective Equality (50% point in the S curve of TOJ) was different for both flash and click pairs. These results suggest that TOJs benefit from stimulus properties such as abrupt transience while simultaneity judgments are agnostic to these abrupt onsets.

In another study, Fujisaki and Nishida (Fujisaki & Nishida, 2005) explored the consequences of temporal frequency in the perception of temporal synchrony. Participants saw a luminance modulated Gaussian blob and listened to amplitude modulated white noise. They had to judge whether the two stimuli were synchronous. In addition to manipulating the lag between the two stimuli, the authors also temporally modulated both the audio and visual stimuli frequencies by convolving them with a repetitive pulse train while varying the frequency of the pulses. They show that people found it harder to judge the synchrony if the pulse train frequencies were higher than 4 Hz in both auditory and visual modalities. These results were robust even for the larger SOA between the stimuli. The authors argue that the temporal limitation cannot be ascribed to low level processing mechanisms in either visual or auditory modalities. Rather, they reflect the bottleneck in processing of a central mechanism located at, or before cross modal comparison. Together, these results suggest that stimuli properties such as abrupt onset and temporal frequency affect temporal processing.

The nature of the task: Typically in the TOJ and SJ tasks, participants have to choose between the two choices, i.e., report whether a stimulus appeared 1st, or 2nd, or whether the two stimuli appeared simultaneously, or not. Accordingly, the observed results in SJ and TOJ are often subject to response biases. For example, it has been shown that arm crossing during TOJ gave rise to reversal of Temporal order judgments (Yamamoto & Kitazawa, 2001). In their experiment, participants had to perform judgments of temporal order and simultaneity with arms crossed and eyes closed. They were presented with successive mechanical stimuli delivered to each of the arms. The reports for temporal order judgments were reversed when the arms were crossed compared to the uncrossed condition. The authors ruled out the possibility of confusion in naming the arms in a subsequent experiment by stimulating just one arm, and asking participants to report the stimulated arm. Here, participants were able to report the stimulated arm with high accuracy even when the arms were crossed. The fact that the reversal in temporal order judgments when arms were reversed suggests a response bias in participant reports. Participants might be using the left / right information to judge the temporal order of the presented stimuli. These results suggest that the spatial location of the stimulus affects the judgment order in tactile stimuli. Interestingly, the reversal only happened with TOJs and not with Simultaneity Judgments for tactile stimuli, thus suggesting that the nature of task and stimuli affects the processing of temporal information.

In one other early study conducted by Frey (Frey, 1990) on multimodal temporal order judgments, participants were asked to report temporal order while attending to one modality. The results indicated that participants tended to report the “attended stimulus first” when asked to indicate which stimulus came first. However, their reports were biased towards “non-attended stimulus first” when asked to report which stimulus came second. These results suggest the impact instructions have on judgment reports. Additionally, Jaśkowski (Jaśkowski, 1993) has also demonstrated the effect response options have on the task. In their experiment, participants performed a TOJ task while attending to one stimulus, and they had to report the order of stimuli as instructed. They manipulated the number of responses to include either two or three alternatives. The results indicated a shift of psychometric functions for the two-response paradigm. They therefore suggest shorter latency (faster processing time) for the attended stimulus. However, this shift vanished in the three-response paradigm. The response distributions obtained were different when the task had two alternatives, compared to when a third “simultaneous” option was available to choose from. Several other studies have pointed out the demands these tasks pose on temporal processing (Arstila et al., 2020; Garćia-Pérez & Alcalá-Quintana, 2012; Machulla, Di Luca, & Ernst, 2016; Mitrani, Shekerdjiiski, & Yakimoff, 1986; Miyazaki, Yamamoto, Uchida, & Kitazawa, 2006; Vatakis, Ghazanfar, & Spence, 2008). Task related properties such as spatial location, and instructions contain order information. As noted above, it is possible that the participants were relying on left -> right in the study conducted by Yamamoto and Kitazawa (Yamamoto & Kitazawa, 2001). Similarly, the instructions presented in (Frey, 1990) study also contain the labels “first” and “second” which imply order and could be contributing to the reports participants made about temporal order judgements. Together, these results demonstrate the effects the nature of the task has on the response judgments.

Attention to a modality speeds up the perception of any stimulus presented in that modality, a phenomenon called ‘prior entry’ (Titchener, 1924; for an extended review see Spence & Parise, 2010a). Stelmach and Herdman (Stelmach & Herdman, 1991) showed that for a given set of 2 stimuli with two equal onset times, the attended stimulus was perceived to have appeared first compared to the unattended stimulus (also see Sternberg, Knoll, & Gates, 1971; Sternberg, Knoll, & others, 1973). In their experiments, participants were instructed to perform a temporal order judgment (left / right disc appeared first) while fixating the center of the screen. They were presented with cues on either left, center, or the right side of the fixation instructing them to attend covertly to those locations. Participants’ reports were significantly biased to the attended locations as having occurred even when that was not the case. The authors further show that these attentional effects persist even when participants were given a choice between reporting as left first, right first, or simultaneous, thus demonstrating the robustness of the effect directed attention on a ternary TOJ task. However, Jaśkowski (Jaśkowski, 1993) failed to replicate the findings of (Stelmach & Herdman, 1991). One reason for this discrepancy may be that participants in (Stelmach & Herdman, 1991) used the simultaneous option far less than in Jaśkowski's (Jaśkowski, 1993) study. Alternatively, it could be that the ternary task in itself could involve response biases. And that these biases are well manifested in (Stelmach & Herdman, 1991) compared to (Jaśkowski, 1993) studies because of the relatively higher number of subjects (Stelmach & Herdman, 1991) study had. Thus suggesting that attentional effects might be confounded with response bias. Specifically in the studies investigating the effects of prior entry on TOJ, participants might have confused left/right with attended/unattended locations. Mostly because these studies used different means to deliver stimuli. For example, the auditory stimuli were delivered using headphones, whereas, the visual stimuli were delivered either on the left/ right of the screen thereby making it easier for the participants to report the attended stimuli by focusing on the left/ right location.

Spence and colleagues (Spence et al., 2001) investigated the effects of prior entry in visuo-tactile modalities while controlling for the location and attention confounds. In a series of experiments, they explicitly asked participants to either attend to visual or tactile modalities. In a given trial, participants saw two stimuli appear on the screen, and they were instructed to either report which modality appeared first, or which side (left/right) had been presented first. This way, if the responses were biased, they should reflect only in one condition (i.e., reporting the side). However, participants tended to report the attended modality / location as having appeared first compared to the unattended condition in spite of this explicit manipulation. These results provide a resolution for the link between “attention” and location related response biases that the previous studies had. They provide stronger evidence for prior entry, i.e., attended modality speeds up processing of temporal judgments in that modality. Similar results have been found for auditory and tactile modalities (Kanai, Ikeda, & Tayama, 2007; Yates & Nicholls, 2009).

Simultaneity Judgments are also thought to be affected by prior entry. For example, Carver and Brown (Carver & Brown, 1997) investigated the effects of attention in judging simultaneity in the visual modality, and found that pairs of stimuli in exogenously cued locations were less likely to be judged as simultaneous across a range of SOAs than were pairs of stimuli in uncued locations. In their experiments, the stimuli were exogenously cued by highlighting the location with a circle before the stimulus appeared at the location. Directed attention to these cues distorted participants’ simultaneity judgments even when both the stimuli (cued and uncued) were presented simultaneously. Similar effects have been reported for somatosensory stimuli (Yates & Nicholls, 2011). Together, these results suggest that prior entry / attentional effects affect Temporal Order and Simultaneity Judgments.

Schneider and Bavelier (Schneider & Bavelier, 2003) further probed into the mechanism by which attention might affect temporal judgments and outlined three possible mechanisms: 1) Attention might speed up sensory processing - which is the core of the prior entry hypothesis 2) Attention might change decision making criteria while leaving the sensory processing unaffected, and 3) attentional cues might leave a neural trace of activation, that indirectly facilitates the processing of temporal judgments. The authors threw support behind the 3rd hypothesis. In other words, they predicted that attentional cues might leave a persisting neural trace behind that might aid in Simultaneity and Temporal Order Judgments. According to this neural trace prediction, the effect of attentional cues should be different depending on the cue type, since exogenous and endogenous cues have different neural traces that persist for different periods of time (Busse, Katzner, & Treue, 2008). Participants in their experiments judged whether two visual stimuli were presented simultaneously. In their experiments, they had one of the stimuli cued either exogenously (by a circle appearing around the stimulus), or endogenously (an arrow at the fixation pointing towards the direction of the stimulus's location). They found that there was a significant difference in participant reports in both the cue conditions. These results support their hypothesis that attentional cues leave a persisting neural trace behind that facilitates sensory processing, and as a result speeds up response judgments in the temporal order and simultaneity tasks.

Recalibration of judgments through exposure to asynchrony: There has been mounting evidence demonstrating that prior exposure and habituation to asynchronous stimuli affects temporal order and simultaneity judgments in participants. Typically in these paradigms, participants are exposed to the stream of stimuli that are asynchronously presented, and they are asked to perform TOJ and SJ in the same modality following the exposure. For example, Fujisaki and colleagues (Fujisaki, Shimojo, Kashino, & Nishida, 2004) investigated the effect of audiovisual asynchrony in judging temporal order. Participants were exposed to a training phase (adaptation) of audio-visual stimuli separated by a set time lag (different lags were tested ranging from -600 to 600 msec). Participants then judged the simultaneity of the given stimuli in the testing phase through a ternary choice task (simultaneous, related but not simultaneous, not related). Their results indicate that the observed PSE values were influenced by the adaptation condition. The PSE in the no adaptation condition was at -10msec (i.e., participants were at 50% chance in reporting the correct order when the sound was leading visual stimulus by 10 msec). The PSE had shifted depending on the asynchronous lags in the adaptation trials (-32msec after adaptation to asynchronous stream of -235 msec lag, and +27 msec for an asynchronous stream of +235 msec lag; negative values indicate sound leading vision).

Fujisaki and colleagues (Fujisaki et al., 2004) also demonstrate that the effects of adaptation to asynchronous stimuli are robust across different tasks. For instance, in one of their experiments participants had to judge whether two balls had streamed through / bounced off of each other. Participants watched videos of two balls bouncing off each other with a sound emanating right at the time of collision. Adaptation during this period altered their simultaneity judgments during ambiguous test trials where the balls either streamed through / bounced off each other, thus suggesting a robust effect of adaptation in simultaneity judgments. Similar effects have been reported in other studies (Di Luca, Machulla, & Ernst, 2009; Hanson, Heron, & Whitaker, 2008; Keetels & Vroomen, 2007; Navarra, Hartcher-O'Brien, Piazza, & Spence, 2009; Stetson, Cui, Montague, & Eagleman, 2006; Vroomen, Keetels, De Gelder, & Bertelson, 2004).

Vroomen and colleagues (Vroomen et al., 2004) also investigated the effect of temporal recalibration on a TOJ task. In their study, participants were instructed to perform TOJ following exposure to audio-visual asynchrony. Their results indicate that the PSE increased with increased audiovisual asynchrony in the training phase.

However, the change in PSE plateaued beyond 100 msec. Relatedly, Fujisaki and colleagues (Fujisaki et al., 2004) study on Simultaneity Judgments also noted a levelling effect in simultaneity judgments after 100 msec. Participants significantly report the two stimuli as not simultaneous, but related for lags above 100 msec. The findings from both (Fujisaki et al., 2004) and (Vroomen et al., 2004) raise an interesting observation about the critical lag separation of 100 msec during the adaptation phase. Vroomen and colleagues (Vroomen et al., 2004) postulate that beyond 100 msec asynchrony, the signals from the two sources are not likely perceived as paired anymore, thus preventing the need to recalibrate. Furthermore, these results raise interesting questions about the effect temporal recalibration has on the temporal integration window.

Navarra and colleagues (Navarra et al., 2005) further tested the limitations of temporal integration window on two fronts: 1) Is the temporal integration window specific to stimuli within a given modality pair? 2) How long is the temporal integration window? In their experiments, they had participants exposed to both complex and simple stimuli within the same modality (such as watching videos of a hand playing the piano / video tape featuring a speaker pronouncing a list of words) played either synchronously, or with varied asynchrony (300 msec, 1000 msec). While participants had to monitor these videos, they were asked to judge the temporal order of pairs of auditory (white noise bursts) and visual stimuli (flashes) that were presented at varying stimulus onset asynchronies (SOA). This design differed from other studies in that judgments were made during the exposure, and the complexity of the stimuli varied in recalibration and temporal order judgment tasks. They show that exposure to asynchronous complex stimuli (piano /speech) can also produce recalibration effects on simple stimuli (white noise / flashes). In their analyses, Navarra et al., 2005 found that the JND of the fit psychometric curves changed for adaptation to asynchronous vs. synchronous conditions. However, the estimates for PSE did not change much in both the conditions suggesting that the temporal integration window is widened following exposure to asynchronous stimuli. Further, the recalibration effect vanished for asynchronies after 300 msec suggesting that exposure to asynchronous stimuli modifies the temporal window of integration only to a certain extent (similar to the results of Fujisaki & Nishida, 2005; Vroomen et al., 2004).

In contrast to these findings, Hanson et al., 2008 found that JND did not change much with recalibration. However, they found that the PSE estimates did change. They had participants perform TOJ across audio visual, audio tactile, and visuo-tactile modalities in both baseline (no exposure) and asynchronous exposure conditions. Their results indicate that PSE shifts happen across all modalities, however, the JND (the sensitivity to identify stimulus order) does not change much. One reason for this discrepancy has to do with the nature of the task. Navarra et al., 2005 used online judgments, whereas Hanson et al., 2008 had participants report retrospectively. The same pattern of results about JND and PSE shifts were observed in Fujisaki et al., 2004 study which also used retrospective judgments. These results highlight the significance of task type in influencing the observed results in TOJ and SJ tasks.

The exact mechanism by which asynchronous exposure affects temporal processing / temporal integration window is not clearly understood. Two possible candidate hypotheses that explain the effect of recalibration are: 1) Our perceptual latency is decreased following exposure to asynchrony. This implies faster detection and processing of the stimuli. Alternatively, 2) the decision making process is altered. This implies that the sensory processing / perceptual latency is not affected, however, the decision making criteria are affected. The studies discussed thus far have provided evidence in terms of the changes in estimates of JND and PSE for the fit psychophysics models. The changes in these parameter estimates across the experimental manipulations do not provide a clear distinction between the above mentioned candidate hypotheses for the underlying mechanism of temporal recalibration. Firstly, the parameter estimates are describing the models fit to the data, and are not directly tapping into the underlying mechanisms which can be used to shed light between the above mentioned two distinctions. Secondly, both accounts 1 and 2 can result in the same parametric fits, thus providing an inverse problem of sorts - i.e., changes in the parametric fits can be either because of changes in decision making, or changes in perceptual processing.

Di Luca and colleagues (Di Luca et al., 2009) attempted to dissociate between the two candidate hypotheses of temporal recalibration on the perception of temporal order judgments. They investigated the effect audio-visual asynchrony has on temporal processing by having participants exposed to asynchronous audio-visual stimuli that were spatially separated. They were then tested on audio-tactile, and visuo-tactile modalities. They hypothesized that if recalibration alters the perceptual latency instead of the decision mechanism, transfer to another modality should reflect processing changes in the perceptual latency. Since it is possible that the decision criteria might differ across the modalities, any transfer of recalibration effects across modalities would provide support for the hypothesis that the perceptual latency of stimulus processing is affected by temporal recalibration. Accordingly, they found that participants' estimates of visual-tactile modality judgments were altered after exposure to audio-visual asynchrony, but not the auditory-tactile judgments. These results support the first hypothesis that visual processing speed is altered due to recalibration. However, in a subsequent experiment, they found that both audio and visual perceptual latencies were altered when the participants judged the temporal order for co-located stimuli using headphones. The authors explain these results by postulating that the trust (the amount of confidence) the brain puts in a modality in order to make inferences about temporal order is dependent on the perceptual latencies. Modalities with more variable perceptual latencies are trusted less. Therefore, when one modality has variable perceptual latencies (say vision in audio-visual modality), any transfer modality judgments (such as visuo-tactile) would be affected because of the less trustworthy nature of visual modality.

Similarly, Navarra and colleagues (Navarra et al., 2009) investigated whether adaptation to asynchrony modulates the speeded processing of a modality using Reaction Time measures. They postulated that temporal recalibration in the AV modality raises two possibilities 1) The observed temporal shift is towards audition 2) Or towards vision. In terms of processing, they hypothesized that one modality is faster than the other. If this were true, participants should be quick in detecting the stimuli as and when presented. They therefore asked the participants to perform an RT task (i.e., press a button when they hear the sound, or see a stimulus, as quickly as possible). They found that RTs for sound are altered in both audio leading and video leading conditions of AV asynchronous exposure. However, the RTs for videos are not changed much. While these results provide some evidence for speeded processing (similar to Di Luca et al., 2009), neither of the studies are completely able to rule out decision criterion shifts because of the exposure.

Together, these experiments demonstrate the effect of temporal recalibration in simultaneity and temporal order judgment tasks. Specifically, the results from (Fujisaki et al., 2004; Vroomen et al., 2004; Navarra et al., 2005) are agnostic about the nature of representations used in temporal order judgments. They show that temporal recalibration is a robust phenomenon that can be manifested across tasks involving various complexities, and that the recalibration effects plateau beyond a certain value of asynchrony between the stimuli during the exposure phase. However, they do not provide a distinction between the processing speed and decision criteria accounts.

2.4. Mechanisms of temporal processing TOJ and SJ: More than one?

A secondary but related question that we explore in this section concerns whether temporal order and simultaneity judgments are the outcome of a single mechanism. The existing consensus on this is rather divided. Earlier studies investigating the underlying mechanisms of temporal perception questioned if there is more than one system at work for perceiving temporal properties. For example, is the perception of non-simultaneity necessary and/or sufficient for perceiving temporal order?

Early studies conducted by Hirsh (Hirsh, 1959) had shown that there is more than one perceptual system involved in processing temporal information. In their experiment, participants had to identify the number of tones as well as judge the order in which they were presented for various SOAs. They found that participants were accurately able to identify the number of tones presented within a temporal interval of 2msec, but not the order in which they were presented. At least 20 msec of SOA between the two stimuli was needed for accurate temporal order judgments. This result prompted the authors to speculate whether the mechanisms behind simultaneity and temporal order are distinct. Similarly, Mitrani and colleagues (Mitrani et al., 1986) have demonstrated evidence for potential dissociability between TOJ and SJ. In their experiment, participants saw two discs flash at varying SOAs (either both near fovea, or one in the fovea and the other in the periphery). They had to report if the left / right disc appeared first, or if they were simultaneous. Upon analyzing the proportion of left, right, and simultaneous responses made for each of the presentation conditions, they concluded that stimulus onset asynchronies of 30 and 50 msec were not sufficient for identification of temporal order. However, participants were above chance level in reporting whether the discs were presented simultaneously.

Further evidence for the dissociation of the two mechanisms comes from Stelmach and Herdman (Stelmach & Herdman, 1991) who have shown that directed attention affects temporal order judgments, but not simultaneity judgments. These results suggest that there might be more than one mechanism underlying the perception of order and simultaneity. The above mentioned findings have investigated the dissociable nature of simultaneity and order judgments within the scope of a single modality. The existence of multiple mechanisms underlying temporal perception raises important questions about the cross-modal nature of perception. Specifically, how does the existence of multiple underlying mechanisms affect temporal perception across the senses.

Van Ejik and colleagues (Van Eijk et al., 2008) have used a multimodal (audio-visual) approach to investigate the difference between SJ and TOJ. In their study, participants performed SJ and TOJ tasks on two different stimulus complexities (i.e., SJ and TOJ between flash and click pairs, and bouncing ball and collision sounds). They found that the PSS values obtained from the two stimuli complexities for SJ were consistent across modalities while the TOJ judgments were not. These results advocate for the modular nature of the processes that are involved in SJ and TOJ tasks. Similarly, in another experiment, Vatakis and Spence (Vatakis & Spence, 2007) used adaptation to asynchronous audiovisual stimuli to illustrate the independent nature of the mechanisms involved in SJ and TOJ (see also Vatakis & Spence, 2008). It has been shown that exposure to temporally misaligned audio visual speech signals can affect the participants' sensitivity (JND) in the TOJ task, but not the PSS (Navarra et al., 2005; however, see also Vroomen et al., 2004). In their experiment, Vatakis and Spence (Vatakis & Spence, 2007) had participants exposed to asynchronous speech inputs that contained male names. In a given trial they were instructed that they would either have to perform a SJ/TOJ task, or monitor the number of male names in the background audiovisual speech. The audiovisual speech was either synchronous or asynchronous. They show that while the sensitivity (JND) for SJ and TOJ were reduced in the presence of asynchronous background audio visual, the PSS for SJ task was modulated but not the TOJ. These results suggest the dissociable nature of temporal order processing across senses.

However, one common aspect among all the above results is that all these studies have used the same kind of paradigms, albeit in different modalities and with factors manipulating temporal order to draw this conclusion. One limitation of these paradigms is that they (both SJ and TOJ) are prone to response biases. The response biases in TOJ usually affect the estimated PSS, while the biases in SJ task affect the standard deviation (JND) in the SJ task. So it is not entirely clear whether the observed differences in these two paradigms across the findings actually imply the dissociable nature of temporal processing.

Linares and Holcombe (Linares & Holcombe, 2014) have taken a different approach to further provide support for the dissociable nature of the two mechanisms. In their approach they reasoned that if perception of temporal order and simultaneity is required for construction of the duration we experience, then the perceptual latencies measured in TOJ and SJ should correlate with the observed perceptual latency from another task that involves temporal processing, like a duration judgment task. Therefore, in their experiment, in addition to performing the TOJ and SJ, participants were presented with a duration judgment task - where two intervals were presented on each trial, and the observers had to judge which stimulus was longer in duration. They hypothesize that if there is a central mechanism underlying the perception of order, simultaneity and duration judgments, then the responses on TOJ and SJ tasks must be correlated with duration judgments. They show that the perceptual latencies estimated from the duration judgment task do not correlate with that of TOJ and SJ. Linares and Holcombe (Linares & Holcombe, 2014) conclude that each of the temporal tasks might be affected by different biases unique to the task that is responsible for the lack of correlations. Additionally, it has been shown that there are different underlying neural correlates of ERP that get triggered independently for SJ and TOJ tasks (Basharat, Adams, Staines, & Barnett-Cowan, 2018).

In the last decade, there has been mounting evidence suggesting partially shared mechanisms between TOJ and SJ. In principle, a detector comparing the arrival times of both the signals x and y (T_x - T_y) should be able to provide both SJ and TOJ. In this case, the difference in arrival times being different than 0 (or close to a certain threshold) should inform about simultaneity, while the direction of the difference (positive / negative) should inform about temporal order judgments. This suggests that theoretically there could be an overlap of mechanisms between TOJ and SJ. In accordance with this intuition, Machulla and colleagues (Machulla et al., 2016) have shown that SJ and TOJ share the same perceptual representations using audio visuo-tactile stimuli. However, TOJ are prone to biases in the decision making stage as opposed to SJ (Fink et al., 2006; Garćia-Pérez & Alcalá-Quintana, 2012; Yamamoto & Kitazawa, 2001). Central to Machulla and colleagues' (Machulla et al., 2016) claim is the principle of transitivity which supposes that if the TOJ and SJ are operating on pure perceptual representations then they should adhere to the transitivity principle for different modalities. This is because purely perceptual representations reflect processing latencies, and are not prone to biases at decision making stages, and therefore adhere to the transitivity principle. According to this principle, suppose if Audio is leading Video by 'x' msec, and Video is leading Tactile by 'y' msec, then Audio should lead Tactile by 'x+y' msec. They find that the PSS for SJ and TOJ are correlated for audio visual and tactile modalities, however, only SJ adheres to the principle of transitivity but not TOJ. Based on this they conclude that SJ and TOJ share a common mechanism.

Garćia-Pérez and Alcalá-Quintana (Garćia-Pérez & Alcalá-Quintana, 2012) have provided further evidence for this using quantitative modelling of the TOJ and SJ data. In the same vein, Arstila and colleagues (Arstila et al., 2020) have shown that factors such as age, gender, experimental and stimuli dependent variables such as orientation, position, trial order and so on affect responses in unimodal TOJ and SJ tasks. Furthermore, these variables modulate the TOJ and SJ independently suggesting they are partially independent functions. Furthermore, Miyazaki et al., 2016 have used fMRI to investigate the neural correlates of these two tasks, and have shown that both SJ and TOJ implement specific process components. They found that TOJ specific activity was observed in multiple regions that overlap with general temporal prediction networks for perception and motor systems compared to SJ thus suggesting that TOJ requires more processes than SJ. Together, these results suggest that while both simultaneity and order judgments share a common mechanism, they also make use of additional processes in inferring temporal properties.

2.5. Theoretical implications

Having reviewed the results associated with TOJ and SJ judgment, we now turn to questions of theoretical implication. As noted previously, a focus of the discussion to follow will be on the kinds of representations that may or not be implicated by the extant data. So far we have reviewed the Temporal Order Judgment (TOJ), and Simultaneity Judgment (SJ) paradigms, identified several factors that could affect the responses in these tasks, and tried to infer how each of these factors might inform us about the three kinds of temporal representations discussed in the beginning of the review. Additionally, we have also reviewed whether simultaneity and temporal order judgments stem from a single mechanism. However, the implications of these factors concerning temporal processing is still unclear. Specifically, how is our experience of time altered during these manipulations? What kind of representations do temporal processes use? In this section, we will consolidate the findings from the literature described in earlier sections to try and infer if/how our experience of time is altered. We will do so by discussing the implications of the three kinds of temporal representations on the experience of time.

As described earlier in the beginning of the chapter, the three kinds of representations play a crucial role in understanding how we experience time during the temporal order and simultaneity judgment tasks. Specifically, the first kind of representations are the wall clock kind of representations. They represent time directly compared to the other two kinds (i.e., walking example and Reichardt detector). In the following paragraphs, we will group the evidence from the literature into two bins: evidence supporting the first kind, and evidence in favor of the other two kinds of representations.

2.5.1 Evidence favoring the second and third kind of temporal representations

At this point I would like to remind the reader what representations of the second and third kind are: The ***second*** kind of representation would be about time, but it does not use time - like the walking example. Whereas the ***third*** kind of representation would not be about, and does not use time, but can be consulted to make inferences about time - like the Reichardt detector example. Several studies have provided results that favor the second and third temporal representational kinds. For example, numerous studies (Kitagawa et al., 2005; Zampini, Guest, et al., 2005; Zampini et al., 2003) demonstrated that the spatial separation between the stimuli affects the performance in TOJ and SJ tasks, i.e., participants are more likely to report two simultaneous stimuli as non-simultaneous if they are spatially separated. They postulate that spatial separation violates the assumptions of unity. The assumption of unity is a prior expectation that two signals are likely to be simultaneous if they share a common source. For example, in the McGurk effect, we expect that sound to emanate from the lips. Note that this kind of expectation is not representing temporal order directly. Instead, the temporal properties such as simultaneity and order are inferred indirectly through the unity assumption, which is about simultaneity (a temporal property) but by itself is not representing the temporal properties. Thus participants might be using the representation of a second kind to process temporal judgments. Temporal representations of the first kind is ruled out by these results because of the following reason: If the first kind of representations are used in their experiments to judge the order, then spatial separation should not matter because we have a representation of temporal order that is not derived from non-temporal properties.

Results from Fink and colleagues (Fink et al., 2006) study on temporal order judgments suggest that abrupt onsets might be invoking stimulus specific processing mechanisms such as apparent motion (Reichardt detector) that are driving the observed effects in temporal order judgments. These results suggest that participants are using representations that do not represent time, and are usually not about time in order to infer temporal representation, suggesting a temporal representation of a ***third*** kind. Similarly, the results from Van Eijk et al., 2008 demonstrate the dissociability between simultaneity and temporal order judgment tasks. Furthermore, the evidence from Machulla et al., 2016 suggests that temporal order judgments might be prone to decision making biases that could be dependent on stimulus specific factors. For example, participant responses in inferring temporal properties such as order are affected by the type of instructions given (e.g.: which stimulus appeared first; which stimulus appeared second), the number of choices they have to choose from (e.g.: choosing between 1 appeared first / 2 appeared first vs. 1 appeared first / 2 appeared first / both appeared simultaneously), task specific response biases (for e.g.: participants might be relying on spatial directions left -> right in reporting the order), reversal of arms (see: (Frey, 1990; Jaśkowski, 1993; Stetson et al., 2006; Yamamoto & Kitazawa, 2001) for e.g.). Notice that these are all representations that do not represent time, but can be the basis for a temporal representation.

Similarly, the literature on prior entry suggests that directing attention to one of the stimuli speeds up the processing of that stimulus (Jaśkowski, 1993; Spence & Parise, 2010; Spence et al., 2001; Stelmach & Herdman, 1991), and further that directed attention leaves a persisting neural trace that might facilitate temporal order judgments (Yates & Nicholls, 2011). Finally, TOJ and SJ are affected by recalibrating our experience to asynchronous information processing (Hanson et al., 2008; Keetels & Vroomen, 2007; Navarra et al., 2005; Stetson et al., 2006; Vroomen et al., 2004). Collectively, these findings suggest that temporal properties such as order and simultaneity are inferred / consulted from non-temporal representations, and/or from the representations that are not directly representing time information. In the following section, I speculate existence of temporal representations of the first kind (wall clock example) being used in temporal order and simultaneity judgments.

2.5.2 Speculative evidence favoring the first kind of representation

Collecting evidence that clearly demonstrates the existence of the first kind has been hard given that this type of representation directly taps into our perceptual experience. Furthermore, isolating the effects of conception, i.e., higher order cognition, from our perceptual experience has been a difficult task. I therefore review the evidence by speculating and trying to identify the existence of temporal representation of the first kind.

Typically, studies investigating whether our experience of time is fundamentally altered by cognitive manipulations (e.g.: directed attention, temporal recalibration, etc.) have quantified the robustness of these effects from the manipulations on other cognitive tasks. At the core of their hypotheses is the assumption that if our perceptual experience changes, it should be generalizable across a variety of cognitive tasks that do not necessarily involve a time processing component, but rely on perceptual experience.

For example, Navarra et al., 2009 have shown that participants' performance improved significantly in a reaction time task involving detection of sounds / visual stimuli - following adaptation to temporal recalibration (where the asynchrony between audio and visual stimuli was manipulated). This improvement in performance in an orthogonal task - that does not necessarily involve judging temporal order and simultaneity - suggests that the processing of stimuli might be altered because of temporal recalibration. If temporal properties were represented using the first kind, and temporal recalibration affected these representations, it would explain why the performance in an orthogonal task was also affected. Similarly Di Luca et al., 2009 have shown that the temporal recalibration effects obtained from adaptation to asynchrony in one modality pair (e.g.: audio-visual) also alters the judgments on other pairs involving the original modalities (e.g.: audio-tactile and visuo-tactile). In another study, Fujisaki and Nishida (Fujisaki & Nishida, 2005) manipulated the flickering rate of the stimuli (both audio and visual) in a temporal order judgment task, and found that participants had difficulty judging the temporal order for a flickering rate around 4Hz. This was true for both auditory and visual stimuli. Their results hint at the presence of a central mechanism for processing time, and that the 4 Hz flickering rate is somehow disrupting this mechanism by acting as a bottleneck. Speaking of the existence of a central mechanism, Machulla and colleagues (Machulla et al., 2016) have also shown that both SJ and TOJ share a common perceptual representation using cross modal temporal judgment tasks. These cross modal studies are pivotal in terms of speculating about the nature of representations employed to infer temporal properties.

Particularly, if temporal judgements were biased by factors such as decision making, it need not necessarily be true that the judgments in other modality pairs also get affected by the same factors. On the other hand, it is possible that sensory processing biases might affect judgments in other modality pairs. For example, a visual sensory bias in judging temporal order of audio-visual TOJ tasks might also affect the judgments in visuo-tactile tasks. These sensory processing biases can sometimes be classified as the third kind of temporal representations. Consider the case of how selective attention affects visual processing for example. It has been shown that selective attention is differential in top and bottom visual hemifields (Abrams, Nizam, & Carrasco, 2012). Therefore, if such a sensory processing bias is used to compute temporal order in a modality pair, the representations that are consulted to infer order are not going to be explicitly about time, and do not represent temporal properties by themselves. And it is very likely that these sensory processing biases might also be responsible for cross modal effects of temporal judgments. While these studies do not actively provide evidence for the existence of a clock like representation, they rule out the representations of the second kind, i.e., representations that are not directly about time, but can be used to infer temporal properties. However, it is unclear whether representations of third kind are consulted in making temporal order judgments in these tasks.

In another study by Vroomen and Keetels (Vroomen & Keetels, 2009), it has been shown that presenting sounds before and after a target changes performance in a four-dot masking task (aka Object Substitution Masking OSM). See Figure 3 for the task design

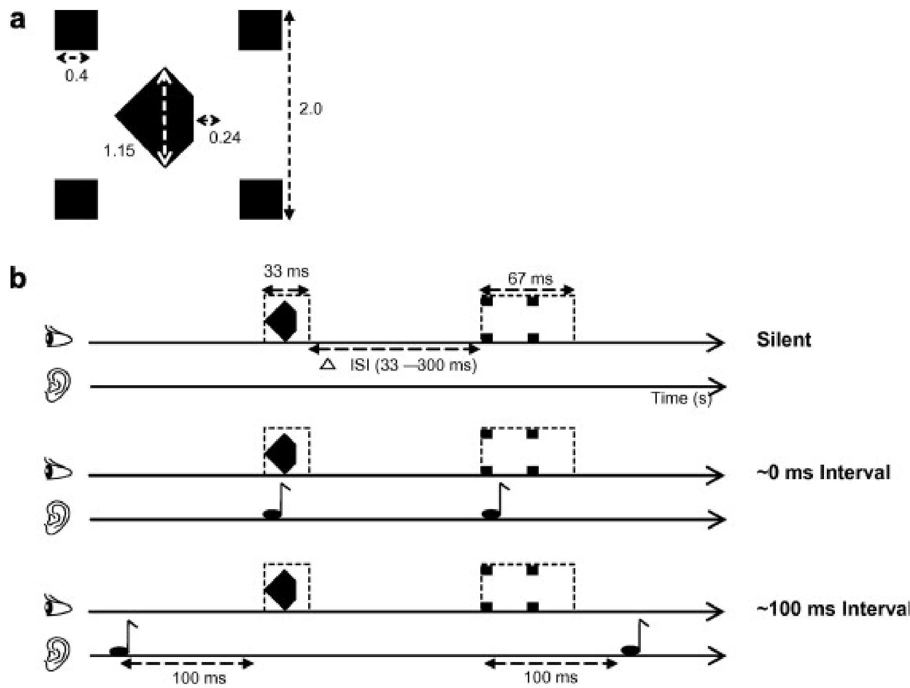

Figure 3 : Sounds change four dot masking (Vroomen & Keetels, 2009)

Experimental design of (Vroomen & Keetels, 2009)*. Participants had to judge whether the left / right portion of the target is missing in an object substitution masking paradigm. Target and the mask appeared along with sounds presented with varied SOAs (0, 100 msec) intervals.*

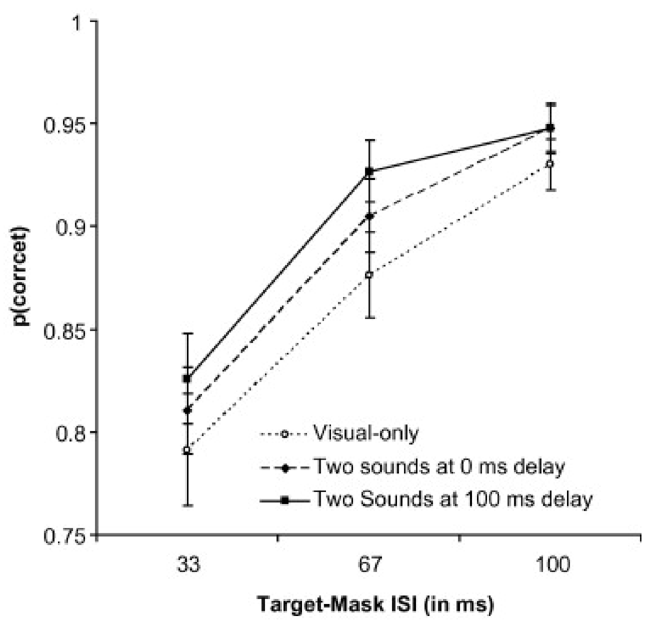

Figure 4 : Results from (Vroomen & Keetels, 2009)

Detection performance in the study improves in the two sounds condition compared to just the visual condition alone.

Typically, people fail to recognize the target that is followed up by four-dots (Enns & Di Lollo, 1997) in the classic object substitution masking paradigm. It takes time to process information presented on the screen. Thus, a given stimulus usually masks the target information when both of them are presented very close to one another in time. In spite of the four dots never overlapping the target pixels on the screen, participants are unable to perceive the target letter. Gestalt grouping mechanisms of perception might be at play in trying to render the four-dot configuration as an effective mask in this paradigm. In the context of temporal processing, Oyama and Yamada (Oyama & Yamada, 1978) has shown that there exist similar mechanisms in judging temporal order, perceptual grouping, and masking. Additionally, it has also been demonstrated that we have difficulty perceiving the temporal order for information that is usually perceived together (e.g.: lip movements and the sound emanating) (Vatakis et al., 2008; Vatakis & Spence, 2007, 2008). One reason this might happen is because we are used to perceiving the two streams as simultaneous. Therefore, if the sounds presented before the target and after the mask create audio visual binding, then they should pull the visual stimuli farther apart in time, and separate the target and mask. This should be reflected in improved detection performance. Vroomen & Keetels, 2009 show that by presenting the sound before and after the stimulus and the mask, target detection performance is increased (Figure 4). Of course, there is a concern that the first sound might be used as a cue to process the target, and thus improve the performance. Vroomen & Keetels, 2009 address this issue by manipulating the second sound. They argue that if the first sound is being used as a cue to process the target, then presenting the second sound should not matter in the increased performance. However, the authors demonstrate that target detection performance is lower for the one sound (no second sound) condition, compared to the two sound conditions (although the difference is small, it is significant). This is an interesting result because it takes a fundamental aspect of the temporal processing (i.e., unity assumption), applies it to an orthogonal task (OSM), and shows that by binding auditory and visual cues, people are able to pull them apart in time and thus improve performance in the object substitution masking paradigm. Although it should be noted that improved performance in this task does not necessarily mean improved perceptual experience since participants had to judge whether the right / left portion of the target is missing in this task. While changes in perceptual experience would reflect an improvement in left / right judgments in this task, the vice versa is not necessarily true, i.e., the improvement in responses may or may not inform us about the perceptual experience. Although it should be noted that this design minimizes the effects of other cognitive factors and biases associated with temporal perception by possibly tapping into the contents of the perceptual experience. Together, the above mentioned evidence collectively is suggestive evidence of the existence of the temporal representation of a first kind (i.e., clock).

2.6. Summary & conclusion

In this tutorial, we reviewed literature investigating the temporal properties of temporal order and simultaneity in perceptual experience. Specifically, we explored at length whether these temporal properties are represented directly in our perceptual experience, or if instead they are derived from the representations of other contents in our experience. The verdict is divided, thus providing some support for both accounts. One major shortcoming in this research has to do with the nature of the paradigms.

Both Temporal Order Judgments and Simultaneity Judgments are subject to task specific biases. In these tasks, participants are asked to either report the order of the stimuli, or whether the two stimuli have been perceived simultaneously. These questions do not necessarily reflect the true temporal nature of our perceptual experience since they do not directly probe our perceptual experience. Future studies could / might address these limitations by probing directly into the contents of our experience in order to strengthen predictions about existing psychological theories on the experience of time - with an emphasis on the representational nature of the temporal experience. The representational nature of the temporal experience is crucial in understanding the content of the present that we experience in time. The next chapter concerns the contents of a visual moment in time. In particular, I will investigate how a visual moment in our experience does not reflect a visual moment in the mind-independent world.

3

Eccentricity Dissociates Time and Space in the Construction of a Visual Moment

3.1 Introduction

We intuitively conceptualize how our perception unfolds / is structured in time in units or moments. These moments are often described metaphorically as snapshots or frames (or coffee spoons, in the case of J. Alfred Prufrock), suggesting that *right now* is a different moment from the moment which just came, and the moment which will immediately follow. Such a conception leaves much to investigate. For example, how long is a moment? Is a moment cross modal? And how do moments combine into extended streams of consciousness? Here I consider a more tractable but surprisingly unaddressed issue: How does a moment combine objects and events from different locations in space? Specifically, if two events take place simultaneously within an observer's field of view, but in different locations, does the observer necessarily become aware of those events as happening at the same time?

To clarify, an analogy between a camera and the visual system is useful. A camera frame includes only objects that were present in a scene during the milliseconds that the camera's shutter opened and closed – neglecting the speed of light, which is relevant if we are photographing the night sky. If two objects are in the same photo, then they must have been simultaneously present when the photo was taken. If two objects entered the viewable scene at the same time that the camera image was captured, then both objects will *always* appear in the frame. Of course, the visual system is not a camera and it is therefore possible that these rules do not apply. Whereas a camera passively collects input—none of it recognized without a viewer to look at the image— the visual system actively processes its input; what someone sees is the *output* from a processing pipeline. Bottlenecks, competition for access, limited attention and working memory (e.g.: Baddeley, 1992; Luck & Vogel, 1997; Nakayama, 1990; Posner, 1980; Raymond, Shapiro, & Arnell, 1992; Wolfe & Gray, 2007; Zhang & Luck, 2008) conspire to make perception a simulacrum of the external environment at a given moment, with inaccuracies such as mis-bindings (Bae & Flombaum, 2013; Hollingworth & Rasmussen, 2010) and even whole objects missing (Drew, Võ, & Wolfe, 2013; Simons & Chabris, 1999) .

It is therefore possible that two objects entering a scene simultaneously are not always perceived simultaneously, and even that a perceived moment includes objects that *never* appeared together in the external world. In other words, perceived moments may not always correspond to actual moments in terms of their constituent objects. I sought to investigate this possibility. Specifically, I anticipated that two objects could appear simultaneous in a perceived moment (i.e., to a viewer) even if they were *never* present simultaneously in reality.

3.1.1 Past Evidence for Temporal Uncertainty

Prior motivation for this hypothesis can be found in the experimental literature under topic headings that include prior entry, simultaneity perception, and temporal order judgement (Frey, 1990; Jaśkowski, 1993; Stelmach & Herdman, 1991; Sternberg et al., 1971; Saul Sternberg et al., 1973; see Spence & Parise, 2010b for a review on prior entry; and see Vroomen & Keetels, 2010 for a review on perception of temporal order). Almost without exception, experiments in these areas ask participants to supply judgments about two discs that can be identified on the basis of relative position. For example, a typical temporal order experiment would ask, ‘Which appeared first, the disc on the right or the one on the left?’ (e.g., Rutschmann, 1966). The results demonstrate uncertainty about appearance order at short intervals. Similarly, experiments on prior entry suggest that a disc which appears in an attended location tends to be reported as appearing *before* a disc which appears in an unattended location (e.g., Jaśkowski, 1993; Stelmach & Herdman, 1991). And similar experiments suggest that observers will sometimes report two discs as having appeared simultaneously even if there was actually a brief lag between the onset of the first one and the second (e.g., Rutschmann, 1966; Stelmach & Herdman, 1991; Sternberg et al., 1971; Sternberg et al., 1973).

Several caveats should accompany these results, which I will return to in the General Discussion. For current purposes, a key feature of these past experiments is the demonstration of temporal uncertainty around the onsets of objects. Two key limitations are that the experiments referenced all ask participants directly about temporal order (e.g., ‘Which disc onset first?’) and they make inferences about perceived simultaneity from aggregate responses analyzed psychophysically. These approaches are confounded with many biases as discussed in Chapter 01. I sought methods that avoid such approaches.

A recent study by Jovanovic & Mamassian (Jovanovic & Mamassian, 2020) also provides support for differences in temporal processing between periphery and fovea. In their study participants were asked to explicitly report when a stimulus was presented within a fixed temporal interval rather than comparing the relationship between fovea and periphery. They found that participants have a tendency to report events in the periphery as happening earlier. More germane still, for current purposes: none of the referenced experiments demonstrate that two objects can be perceived as being present simultaneously even if they were never present at once. When simultaneity misperception has been inferred in past experiments, it is always about misperceived *onsets* for items that eventually coexist in the stimulus. I sought to investigate whether an observer might perceive two items as co-occurring when they actually never overlapped in time.

3.1.2 Illusory Co-occurrence in Rapid Serial Visual Presentation (RSVP)

To achieve this requires a paradigm in which observers report what they see at a given moment. Rapid Serial Visual Presentation (RSVP) is just such a paradigm, and one where prior research has suggested limitations on rapid temporal processing. In classic experiments, participants watch a stream of letters appear serially at fixation, one letter replacing another quickly (e.g., a rate of 200ms). At some point during the stream, a circle will appear surrounding one of the letters, and the task would be to report the letter that appears with that cue. Early accounts of performance focused on attentional bottlenecks in the context of manipulations that asked observers to report more than one target over the course of a trial (Chun & Potter, 1995; Raymond et al., 1992). More recent accounts have emphasized probabilistic uncertainty about temporal order: that observers represent something like overlapping distributions that describe the presence of each letter in the stream (Vul, Hanus, & Kanwisher, 2009). Important for current purposes is that participant responses tend towards normality, centered on the letter that appears together with the outline cue, and with errors extending to the following and preceding letters. It is therefore possible that the paradigm reveals occasions of misperceived simultaneity between a cue and a letter that were never present together.

A complication is that typical studies rely on cues that circumscribe (and therefore overlap) a target spatially, leaving open the possibility that masking or mis binding or afterimages, among other factors, could produce misreported detection. Requiring the detection of multiple targets in a stream further complicates the interpretation of past results with respect to perceived simultaneity. I therefore adapted a bare-bones version of the paradigm to address the question of whether (and why) an observer might misperceive as simultaneous two objects that were never present together.

3.1.3 A Directional Hypothesis: Eccentricity Speeds Entry to Visual Access

The bare-bones RSVP paradigm that I employed was designed to test a specific hypothesis about when and why simultaneity could be misperceived. Specifically, I was interested in how a moment ‘in the visual now’ combines information from across the horizontal extent of the visual field.

Sometimes considered a bug, sometimes a feature, the density of photoreceptors in the human retina is radically nonuniform. Central fovea is mostly all cones (Kolb, 2011). While rods are distributed throughout, their density also declines dramatically with increasing eccentricity (distance from the fovea). Whereas the macula (the central portion of the fovea) may contain as many as 150,000 cones per square millimeter, the far ends of the temporal periphery may contain as few as 50,000 rods and cones combined per square millimeter (80-90,000 at the edges of the nasal periphery. This pattern is replicated in the receptive fields and concentrations of visual system neurons spatially mapped to external space. The spatial resolution of human vision is, as a result, relatively low for all except fixated regions of space. This fact and its implications have been widely examined in vision science, in the context of reading for example (Rayner, 1975; Rayner, Pollatsek, Ashby, & Clifton Jr, 2012) as well as the extensive literature on visual crowding (Whitney & Levi, 2011; see Levi, 2008 for a mini-review on crowding).

Less widely considered are the possible temporal implications of nonuniformity in the eye and the visual system. Some research suggests that the effects invert for temporal processing compared to spatial, that temporal resolution is actually *better* in the periphery. Although the evidence is far less developed than for low spatial resolution, I was particularly motivated by one study which found *faster* processing times in the periphery compared to the fovea (Carrasco, McElree, Denisova, & Giordano, 2003). The reasoning behind that study was that integrating information over fewer neurons should happen more quickly, or put more cognitively, that achieving the high spatial resolution of the fovea takes time above what it takes to achieve the coarse spatial representation of the periphery.

I therefore sought to consider the hypothesis that an object appearing in the periphery might arrive in perception faster than an object appearing at fixation, resulting in misperceived spatiotemporal relationships in experienced moments compared to actual moments. To test the hypothesis, I asked participants to fixate the center of a monitor, where RSVP letters appeared. Participants were instructed that at some point during each stream, a white disc would appear briefly at a random location along the screen's horizontal meridian. I used a white disc for simplicity and to ensure that the cue could be resolved even in the visual periphery. Participants were instructed to report the RSVP letter that occurred with the cue in each trial. We could thereby use fact-of-the matter serial position errors to evaluate whether participants systematically misperceived simultaneity for more peripheral (compared to less peripheral) cues.

3.2 Experiment 1: A moment in visual experience stitches together moments from different times across the space

The schematic of the modified RSVP paradigm is shown in Figure 5. As in familiar RSVP tasks, participants were instructed to report the letter that was present when a cue appeared. Critically, however, I manipulated the location of the cue across the visual field. I hypothesized if the visual snapshot of our experience comprises those events[11] which are actually simultaneous in the visual field, then we should not expect any differences in the response distributions that participants make for different cue

[11] Note: The word "events" used in this context is not to be confused with "events" in the event segmentation literature (for e.g.: see (Zacks & Swallow, 2007)). It can be thought of as the information that is being processed

locations. On the other hand, if events from different time points are stitched together into a subjective moment of experience, then we should expect different response distributions for different cue locations. Given the putative temporal processing advantage of the periphery over the fovea, I hypothesized that participant reports would reveal a misperceived simultaneity between cues and letters that were never present together. Specifically, I predicted that peripheral cues would be reported as simultaneously appearing together with a letter from the past in the letter stream. This implies the response distributions for the peripheral cues would be centered in the past compared to the foveal cues.

3.2.1 Methods

Participants

31 Johns Hopkins undergraduates participated for course related credit. All participants had normal or corrected-to-normal visual acuity. The study protocol was approved by the Homewood Institutional Review Board (HIRB). Per standard practice in this lab, all results were immediately deidentified. Demographic data were collected separately and cannot be tracked directly to this or any other experiments in the lab.

Materials

We used an iMac (Retina 5K, Late 2015, Apple Inc, Cupertino, California), and Psychopy3 software to test the participants. Stimuli were presented on a 27 inch display with a refresh rate of 60 Hz (16.667 msec per frame). Participants were seated approximately 55 cm away from the monitor, and the display spanned about [46 x 29] degree visual angle.

Stimuli

Participants pressed a key to start the trial, at which point a fixation cross in the center of the display was replaced by the rapid serial visual presentation (RSVP) of the 26 letters in the English alphabet (order randomized) on an empty black background. Each letter was presented once for a period lasting 3 display frames (approximately 50 msec). The interval between every two letters (ISI) was also 3 display frames. Letters were printed in white and occupied 2 degrees of visual angle horizontally and vertically. Participants were instructed to fixate the cross in the center of the display before launching a trial, and they were told to also fixate the letter stream as it appeared. Fixations were emphasized, but not monitored or enforced.

The task for participants was to fixate the letter stream while also monitoring the horizontal meridian of the display for a cue that would appear once in each trial. At the end of a trial they were told to report the letter from the RSVP stream that they perceived at the time when the cue appeared. The cue was always a white disk (0.5 degree visual angle). It always remained on the screen for only one display frame. The cue appeared along with the 6th, 10th, 14th, 18th, or 22nd letter in the RSVP stream of a given trial. It appeared one frame after the given letter onset and then disappeared after the second frame, so that the letter remained on the display for one more frame after the cue disappeared. A cue could appear in one of 4 positions along the display's horizontal meridian, 2 degrees to the left and right of fixation, and also 10 degrees to the left and right of fixation. A demonstration of the paradigm can be viewed in my recent talk at the annual meeting of the Vision Sciences Society, 2020 (link here: https://youtu.be/JQlGu8vNaOw?t=230). Each participant completed 120 trials. On an average the experiment lasted for 35 - 40 minutes.

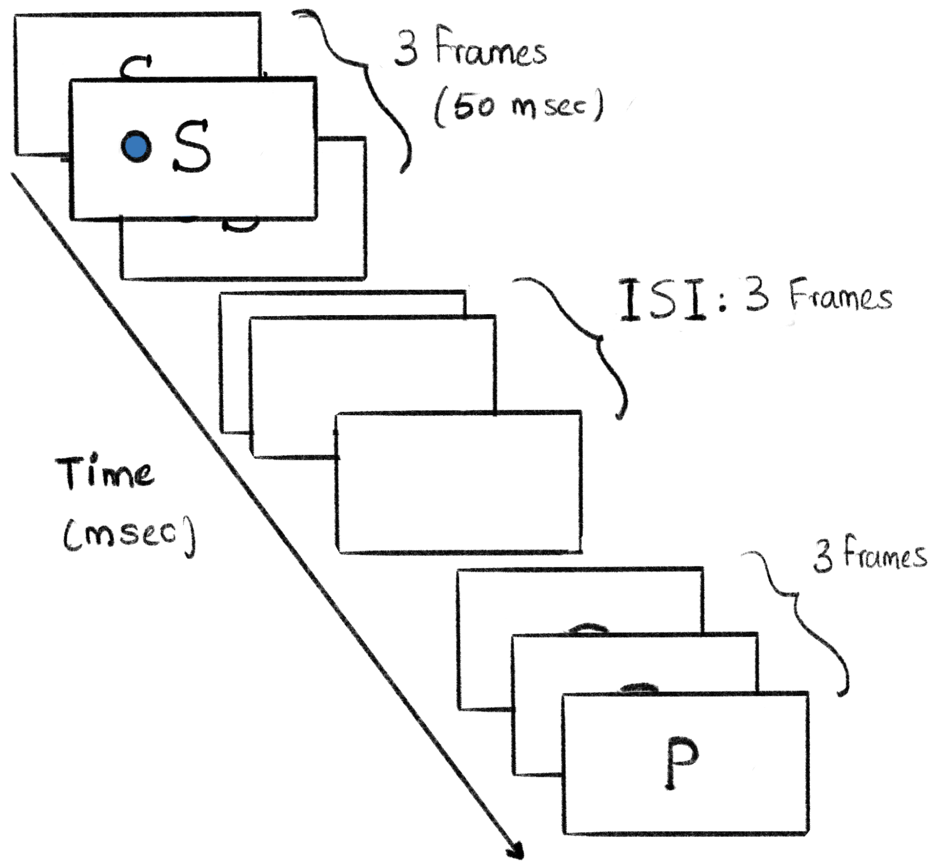

Figure 5 : Modified RSVP task used in experiment 1

Participants have to report the letter present when the cue appears. The cue would always appear for 1 frame duration along with the letter that appears for 3 frame durations. Further, the cue could appear either 2 or 10 degrees to the left / right of fixation. Not to scale.

3.2.2 Results

Participant responses were coded in terms of serial position error (SPE): the relative forward or backward distance between the letter reported and the correct letter answer. In other words, if the participant responded with a letter that appeared along with the cue, the serial position error would be 0, -1 if the reported letter was just before the actual letter with which the cue was presented, -2 indicates two letters prior to the correct answer, and positive numbers indicate letters that followed the cue. This allowed me to pool the responses across the trials for each participant for both the 2 degree and

10 degree visual angle condition as shown in Figure 6. I then computed the average serial position error for each participant for 2 degree and 10 degree response distributions (Figure 7). I found a significant difference between the average serial position error for the 2 degree and 10 degree conditions across the participants $t(30) = 2.33$, $p = 0.026$. In particular, the average serial position error for the 10 degree condition is negative while the average error for the 2 degree condition is positive. Thus, in the 10 degree condition participants more frequently reported letters which appeared *before* the cue, while in the 2 degree condition, they more frequently reported letters that appeared *after* the cue.

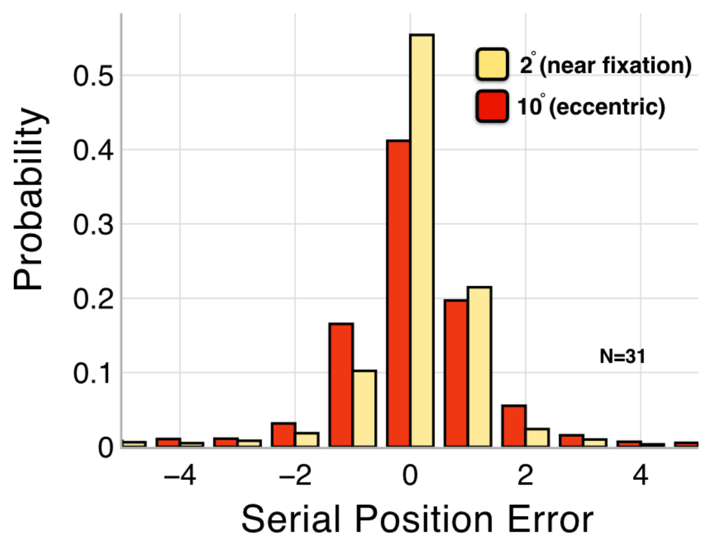

Figure 6 : Result 1 of RSVP experiment 1

Responses made by the participants for the 2 degree and the 10 degree eccentricity conditions. The x-axis indicates the serial position error (the distance of the reported letter from the actual letter).

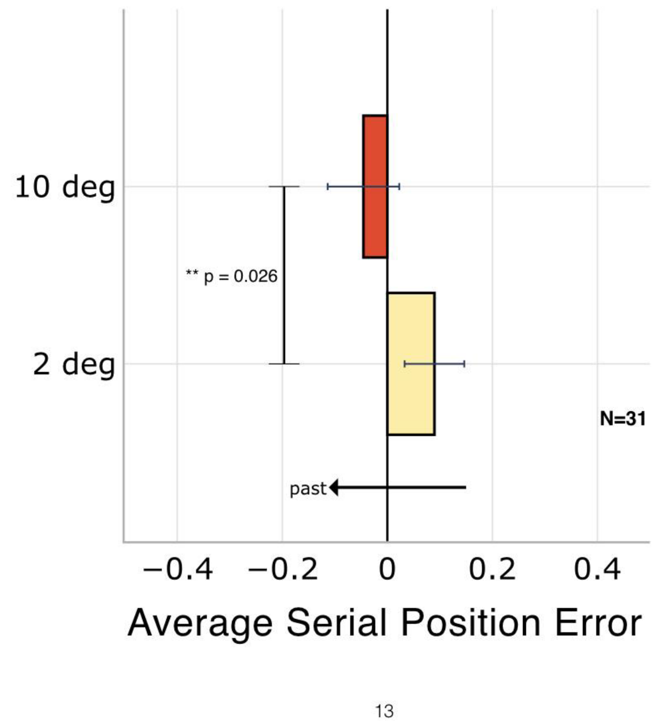

Figure 7 : Result 2 of RSVP experiment 1

Average serial position error for each of the cue eccentricity conditions.

3.2.3 Discussion

In this experiment I investigated whether simultaneous events reach our awareness simultaneously thereby creating a veridical visual snapshot of the external environment. I hypothesized that events in the periphery would reach awareness faster than those in the fovea. Given this, I expected participants to report earlier letters in the stream when the cue was presented peripherally. In line with this hypothesis, the results show that peripheral cues on average are reported with earlier letters in the stream compared to foveal cues. These results suggest that simultaneous events across the visual field are not perceived simultaneously. I tested the robustness of these results through a conceptual replication in Experiment 2.

3.3 Experiment 2 : Conceptual replication

This experiment was a conceptual replication of Experiment 1 with a slight modification. Specifically, I investigated how participant reports changed when the cue was presented in between two letters in the stream, i.e., during the ISI between the two letters. So, technically there was no correct letter for the participants to report as having perceived simultaneously with the cue (see Figure 8 for illustration of the experiment design). If our perception of a moment in time is not uniform across space as suggested by Experiment 1, we should expect similar results in spite of this manipulation, i.e., participants should report earlier letters for peripheral cues compared to foveal cues in spite of having no correct answer.

3.3.1 Methods

Participants:

22 Johns Hopkins undergraduates took part in this study for course related credit. All the participants had normal / corrected-to-normal vision. All the study procedures were approved, and conducted in compliance with the guidelines provided by the Homewood Institutional Review Board (HIRB).

Materials:

The experimental design was the same as Experiment 1 except with the following modifications. The cue was now presented in the ISI between two letters instead of presenting it along with a letter.

Stimuli:

Similar to Experiment 1, participants pressed a key to start the trial, at which point a fixation cross in the center of the display was replaced by the rapid serial visual presentation (RSVP) of the 26 letters in the English alphabet (order randomized) on an empty black background. Each letter was presented once for a period lasting 3 display frames (approximately 50 msec). The interval between every two letters (ISI) was also 3 display frames. Letters were printed in white and occupied 2 degrees of visual angle horizontally and vertically. Participants were instructed to fixate the cross in the center of the display before launching a trial, and they were told to also fixate the letter stream as it appeared. Fixations were emphasized, but not monitored or enforced.

The task for participants was to fixate the letter stream while also monitoring the horizontal meridian of the display for a cue that would appear once in each trial. At the end of a trial, they were told to report the letter from the RSVP stream that they perceived at the time when the cue appeared. The cue was always a white disk (0.5 degree visual angle). It always remained on the screen for only one display frame. This time, the cue appeared during the 2nd frame of the ISI ***after*** the 6th, 10th, 14th, 18th, or 22nd letter in the RSVP stream of a given trial. The cue lasted for one display frame on the screen before disappearing. Further, it could appear in one of 4 positions along the display's horizontal meridian, 2 degrees to the left and right of fixation, and also 10 degrees to the left and right of fixation. An illustration of this paradigm is shown in figure 4. Each participant completed 120 trials. On an average the experiment lasted for 35 - 40 minutes.

Procedure:

The procedure for this experiment was the same as experiment 1.

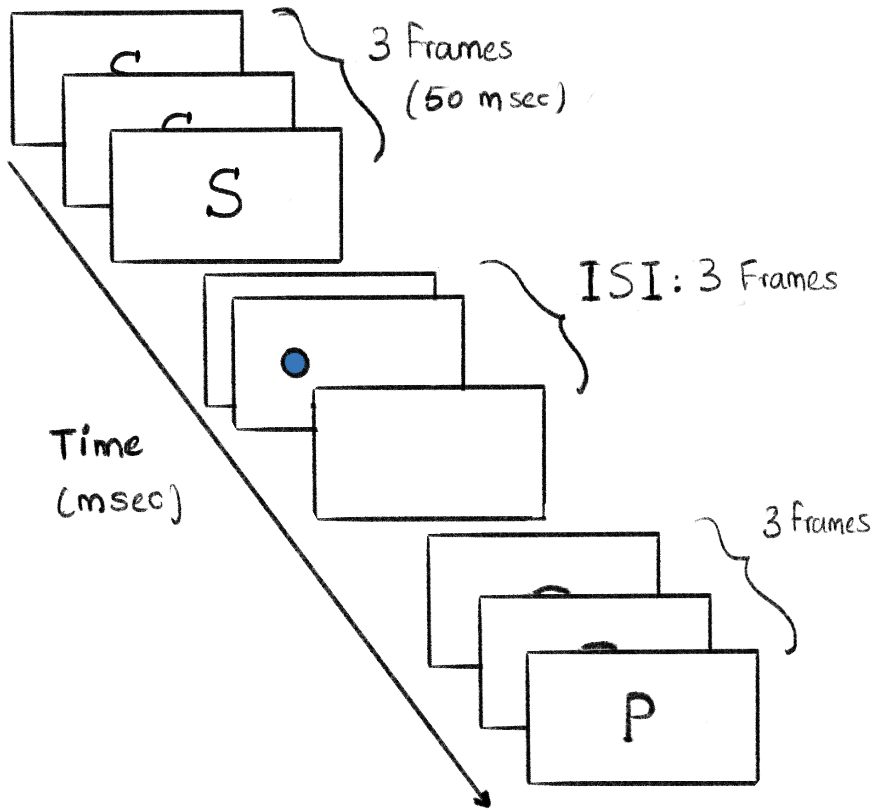

Figure 8 : RSVP Experiment 2 design

Participants have to report the letter present when the cue appears. The letter stream would appear at fixation in a given trial. The cue would appear either at 2 or 10 degrees away from fixation as illustrated in the figure. However, it always appears between the two letter frames such that there is no correct answer. Blue refers to the cue location in the given trial, and it could appear either 2 or 10 degrees to the left / right of fixation. Not to scale.

3.3.2 Results:

Participant responses were coded in terms of the serial position binding errors in the letter stream. In other words, if the participant responded with a letter that appeared slightly before the cue, the serial position error would be -1, and +1 if they responded with a letter that was just after the cue was presented. It should be noted that there is no correct answer in this experimental design since the cue always appeared in the ISI between two letters. In other words, there can never be a serial position error of 0. I pooled responses across trials for each participant for both the 2 degree and 10 degree visual angle conditions. I then computed the average serial position error for each participant for 2 degree and 10 degree response distributions. I found a significant difference between the average serial position error for the 2 degree and 10 degree conditions across the participants t(21) = 3.16, p = 0.005. The average SPE for the 2 degree condition was more positive than for the 10 degree condition. These results are summarized in Figure 9. In other words, participants are significantly reporting more letters from the past for peripheral cues compared to the foveal cues. These results replicate my findings in experiment 1, and confirm the hypothesis that events in the periphery are processed significantly faster than the events in fovea.

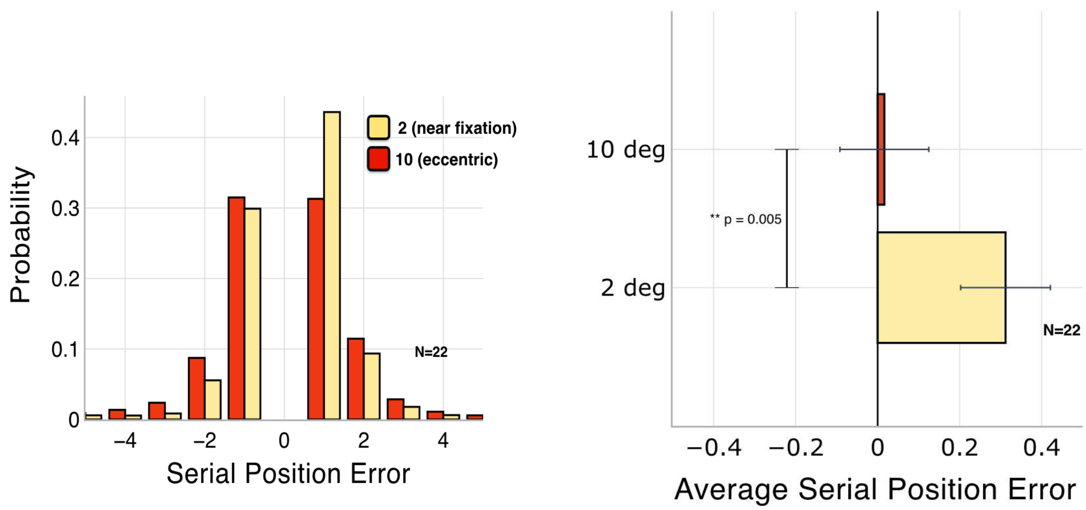

Figure 9 : Results of RSVP experiment 2 – no correct answer

a) Responses made by participants for the 2 degree and 10 degree eccentricity conditions. The x-axis indicates the serial position error (the distance of the reported letter from the actual letter). b) Average serial position error reported by participants.

3.3.3 Discussion

In Experiment 1, participants reliably reported peripheral cues as occurring simultaneously with letters earlier in the stream as compared to foveal cues. Experiment 2, confirmed the robustness of this result. Here the cue was presented in between two letters meaning that there was no correct answer. If the results of Experiment 1 reflect the way our visual system processes simultaneous events, then the same pattern of results should be seen in Experiment 2. In line with this prediction, the results of Experiment 2 exhibited the same pattern as Experiment 1 suggesting that simultaneous events are processed differently depending on their location in the visual field. However, it is possible that the observed results might be driven by attentional and memory factors associated with the task itself. I discuss these below.

Attention and gaze shifts cannot explain these results:

Might our results be due to our attention (and/or eyes) being diverted away from the letter stream and towards the cue when it appeared in the periphery leading to a systematic bias in reporting? I argue that attentional spotlight shifts and eye movements would predict opposite results. Imagine you are trying to identify the target letter from the RSVP stream. When the cue appears in the periphery, you shift your attention / gaze to the cue, and then back to the letter in order to report the current letter. If we are using an attentional spotlight in binding the cue to the letter, then by the time we shift our attention from the peripheral cue back to the letters, we should report the peripheral cue with *later* letters in the stream. So, shifts in attentional spotlight would predict that peripheral cues are perceived as simultaneous with later letters in the stream as compared to (closer) foveal cues. This is the opposite to the results observed in

Experiments 1 and 2 where peripheral cues led to earlier letters being reported. Therefore, it is unlikely that attention / gaze shifts account for our findings.

Prior entry does not explain these results

Prior entry refers to the phenomenon where an attended stimulus enters our awareness earlier as compared to an unattended stimulus (see Spence and Parise 2010 for a review). If participants are attending to the letters as they appeared in the stream, they should be processing the letters earlier compared to the then unattended cue. Therefore, prior entry predicts that participants will report later letters from the stream since the unattended cue will enter awareness more slowly. The results of Experiments 1 and 2 are not consistent with this prediction. Therefore, it is unlikely that our results are explained by prior entry.

Other possible explanations?

The results of Experiments 1 and 2 could be explained by memory driven effects. For example, when the cue onsets on the screen farther apart from the letter stream as in the periphery in Experiments 1 and 2, it is possible that the participants are not confident about the true letter that was actually present. Therefore, they choose to report the most recent letter they have processed up until the cue has appeared, i.e., a letter from the recent past in the stream. This would explain why participant reports for peripheral cues are centered on the letters from the past compared to the foveal cues. Such an account would imply that these immediate memory based responses are manifested because of the physical distance between the two stimuli in Experiments 1 and 2, and not necessarily the eccentricity of the stimuli. I therefore wanted to deconfound eccentricity and distance.

In Experiment 3, I presented the letter stream and the cue at an equal distance from fixation thus dissociating eccentricity from distance (see Figure 10 : RSVP Experiment 3 design for an illustration of the design). I hypothesized that if the observed effects in Experiments 1 and 2 are due to distance between the cue and the letter stream, and not eccentricity, then the same pattern of results should be observed here. Thus, Experiment 3 further serves to demonstrate that the effect seen in Experiments 1 and 2 is specifically due to cue eccentricity as opposed to the relative distance between cue and letter stream.

3.4 Experiment 3: Deconfounding effects of eccentricity from distance

In this experiment, I presented the letter stream and the cue at equal distances from fixation, either each 1 degree or each 5 degrees from fixation (see Figure 10). The actual distances between the letter stream and the cue (2 degrees and 10 degrees) were thus the same as the previous two experiments. I hypothesized that if the results in Experiments 1 and 2 are driven by the distance between the cue and the letter stream, the same pattern of results from Experiments 1 and 2 should be observed in Experiment 3, i.e., larger physical separations between the cue and the letter stream should yield letter reports from the past compared to smaller physical separation. On the other hand, if the effect is due to eccentricity, then we should not expect any significant difference between the two conditions since both the cue and the letter stream are isoeccentric from the fixation.

3.4.1 Methods

Participants

25 Johns Hopkins undergraduates took part in this study for course related credit. All participants had normal / corrected-to-normal vision. All the study procedures were approved, and conducted in compliance with the guidelines provided by the Homewood Institutional Review Board (HIRB).

Materials

All the materials for the Experiment 3 were similar to those of Experiment 1 except with the following modifications. The letter stream and the cue were presented 1 degree and 5 degrees of visual angle apart from fixation on either side of the visual field (see Figure 10). The overall distance between the letter stream and the cue was always either 2 degrees, or 10 degrees of visual angle.

Procedure

The procedure for this experiment was the same as that of Experiment 1. Participants were asked to report the letter that was present on the screen when the cue appeared. Fixation was not imposed, but emphasized during instructions.

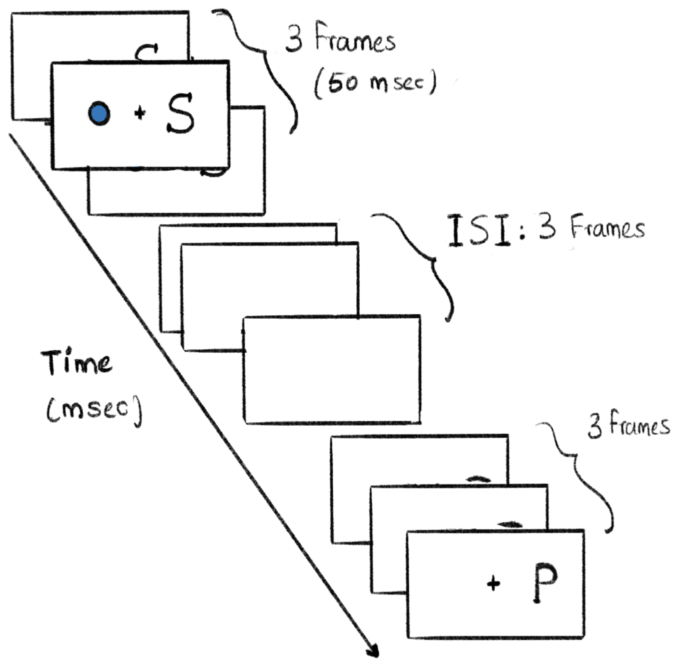

Figure 10 : RSVP Experiment 3 design – controlling eccentricity vs distance

Both the cue and the letter stream appeared equidistant from the fixation at either 1 or 5 degrees eccentricity. Participants have to report the letter present when the cue appears. The letter stream would appear either at 1 or 5 degree to the left / right from the fixation in a given trial. The cue would appear in an isoeccentric location on the opposite of the fixation as illustrated in the figure. Not to scale.

3.4.2 Results

Participant responses were coded in terms of the serial position errors as in Experiments 1 and 2 (here with 0 being a possible coding since there was a correct answer, as in Experiment 1). I pooled responses across the trials for each participant for both the 1 degree (2 degree separation) and 5 degree (10 degree separation) visual angle condition. I then computed the average serial position error for each participant for 1 degree and 5 degree response distributions. On average participants tended to report later letters in the stream for both 1 degree and 5 degree separation conditions but this trend was not significant $t(24) = -1.33$, $p = 0.227$. In line with my hypothesis, I did not find a significant difference between the average serial position error for the 1 degree and 5 degree conditions across participants (See Figure 11 below).

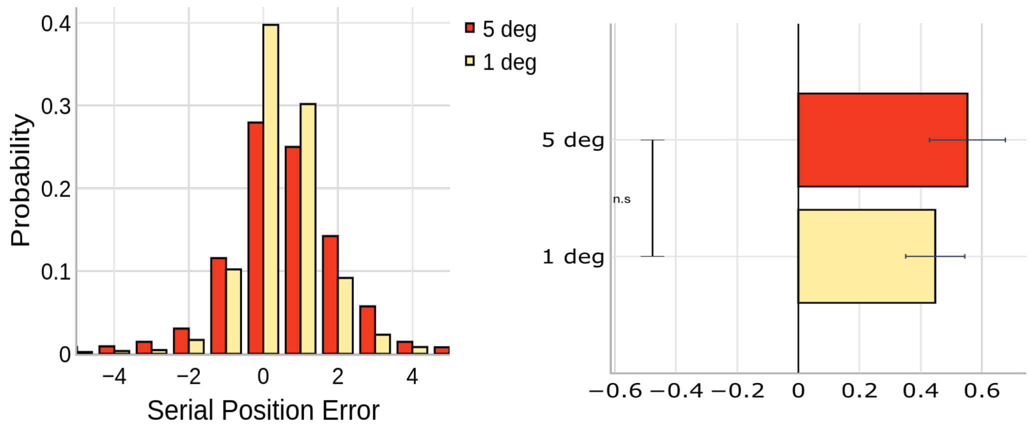

Figure 11 : Results of RSVP experiment 3

a) Responses made by the participants for the 1 degree and the 5 degree eccentricity conditions in Experiment 3. The x-axis indicates the serial position error (the distance of the reported letter from the actual letter). b) Average serial position error reported by the participants in Experiment 3. X-axis here refers to the serial position error.

3.4.3 Discussion

In this experiment, I manipulated the location of both the letter stream and the cue. I hypothesized that if the physical separation between the cue and the letter stream is driving the observed effects in Experiments 1 and 2, the same trend should be observed in Experiment 3 since the overall distance between the letter stream and the cue is the same as that of Experiments 1 and 2. These results indicate that there is no significant difference between the two eccentricity conditions in spite of controlling for the physical distance. The absence of an effect in this experiment demonstrates that the results of Experiments 1 and 2 were due to eccentricity, as opposed to distance.

Overall results from across the three experiments suggest that events in the periphery are processed earlier than events in the fovea. These differences in temporal processing across the fovea and periphery raise an important question as to whether the differences are limited to relative differences in speed or processing, or whether there are other differences in temporal processing, for instance, the perception of duration. I conducted another simple duration judgment task to explore how we perceive duration in both fovea and periphery.

3.5 Experiment 4: Interaction between eccentricity and duration

Experiments 1 through 3 investigated the differences in temporal processing between the fovea and the periphery. Their results show that there is a relative difference in temporal processing between the two regions. Specifically, processing in the periphery happens earlier compared to the fovea. The main aim of Experiment 4 was to investigate the processing differences in these two regions with respect to how we experience duration. Here, participants performed a temporal reproduction task to report the duration of the perceived disc that was presented in the fovea and the periphery (see Figure 12.)

3.5.1 Methods

Participants:

23 Johns Hopkins undergraduates took part in this pilot study for course related credit. All the participants had normal / corrected-to-normal vision. All the study procedures were approved, and conducted in compliance with the guidelines provided by the Homewood Institutional Review Board (HIRB).

Materials:

I used an iMac (Retina 5K, Late 2015, Apple Inc, Cupertino, California), and Psychopy3 software to test the participants. Stimuli were presented on a 27 inch display with a refresh rate of 60 Hz (16.667 msec per frame). Participants were seated approximately 55 cm away from the monitor, and the display spanned about [46 x 29] degree visual angle. In each trial, participants saw a black disc that appeared on the horizontal axis of the screen. They had to report the duration of the disc by pressing and holding the space bar after the disc disappeared. Each disc was about 1.06 degree in diameter, and was present for one of ten durations that ranged between 750 to 1525 msec. The disc could appear at either 3 or 12 degree visual angle on either side of fixation. I used ten different durations ranging from 750 to 1525 msec i.e., 750, 825, 900, 975, 1050, 1125, 1250, 1375, 1450, 1525 msec) . There were a total of 240 trials, 24 for each duration condition, and 60 for each of the manipulated locations. The order of the durations in each trial was randomized, and all the conditions were counterbalanced.

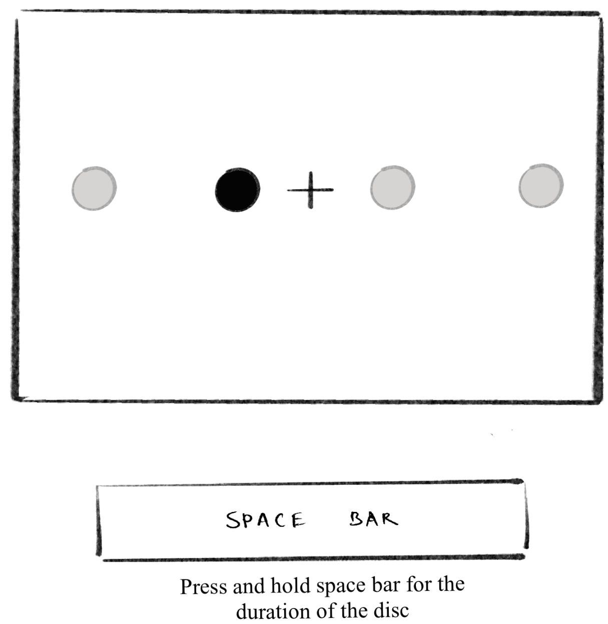

Figure 12: Experiment 4 design – Effects of eccentricity on duration judgments

Participants were instructed to fixate the center of the screen. A disc appeared at different locations on the horizontal axis, and disappeared. Participants had to report the duration by pressing and holding the space bar. Note only one disc was shown on each trial. The black disc here indicates the location of the disc in this current trial. Gray discs indicate all possible locations of the disc in this experiment. Not to scale.

Procedure:

Participants were told that they would be judging the durations of the discs as they appeared across the different locations on the horizontal axis of the screen. They would be reproducing the duration of the disc they saw by pressing and holding the space bar for as long as they thought the disc was present on the screen. They were awarded points in each trial based on how close they got to the actual duration. The number of points they earned in each trial decreased logarithmically as a function of how far away the reproduced duration was from the actual duration. They were told that they would receive double credit if they collected over 1900/2400 total points. In the end, all the participants received double credits irrespective of their performance in the task. Fixations were instructed, but not enforced.

3.5.2 Results:

For each participant, I collected the reproduced duration of each of the manipulated conditions in a given trial. We then averaged the responses for each duration by the manipulated condition across the participants and trials. This is illustrated in Figure 13 below. Overall, participants tended to under-reproduce for longer durations, and over-reproduce for shorter durations. Next I computed the difference between the 12 and 3 degree conditions for each duration condition across all the participants to check if there are any significant differences in reports of duration reproduction at these eccentricities. Figure 14a shows that on average that objective durations at 12 degrees visual angle were over reported compared to the 3 degree condition. We then computed the difference in reports between the objective and the reported durations to see which condition was closer to the objective duration. Figure 14b shows that reports of objects in the periphery are reported closer to the objective duration compared to the 3 degree condition $t(22) = 5.411$, $p < 0.05$. Further, a one sample t-test revealed that the difference in reports for the 3 degree condition were significantly different than 0 $t(22) = 4.31$, $p < 0.005$. However, this was not the case with the 12 degree reports. The reports were not significantly different than 0 ($t(22) = 1.01$, $p < 0.3$) On average there is a difference of 10 msec between the 12 degree and the objective duration, and 40 msec between the 3 degree and the objective duration with peripheral duration judgments being much closer to the objective duration. These results suggest that events in the periphery are reported closer to the objective duration compared to those in the fovea which are underreported.

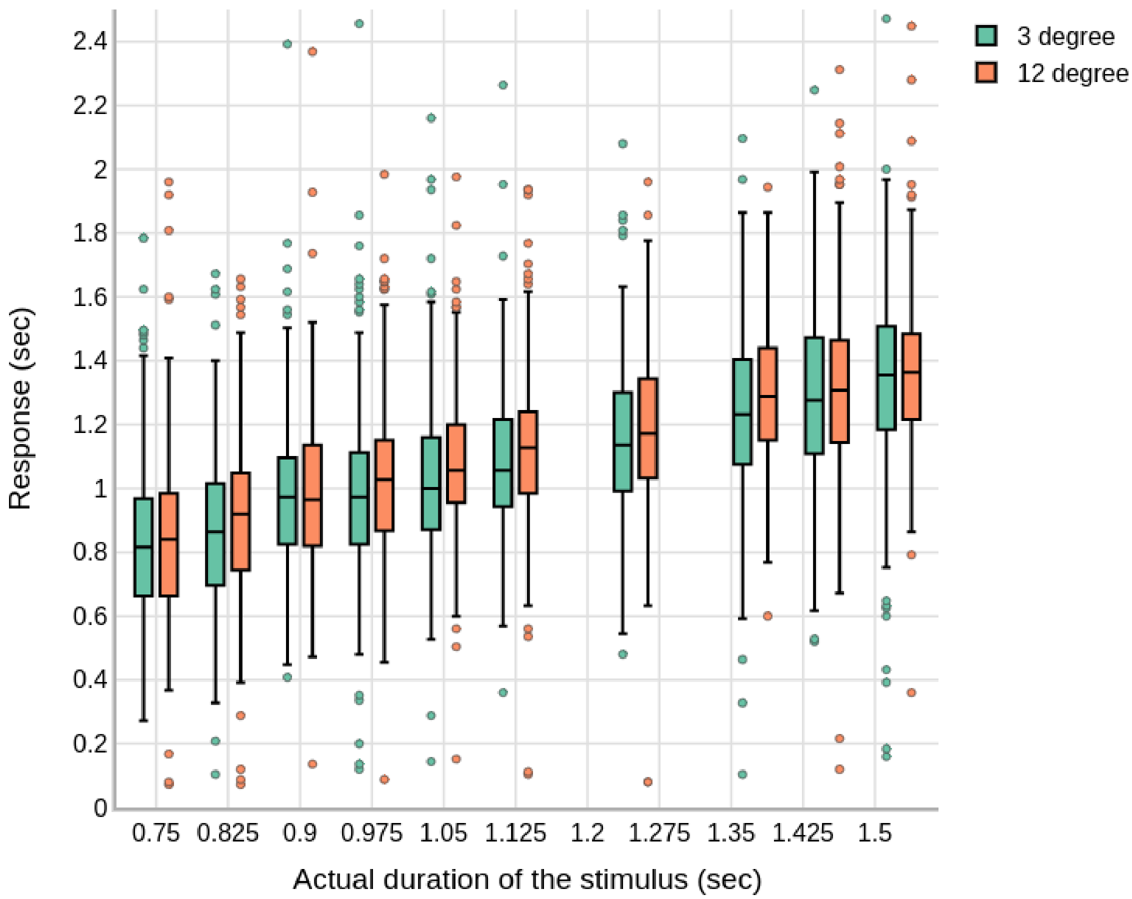

Figure 13 : Raw data from experiment 4

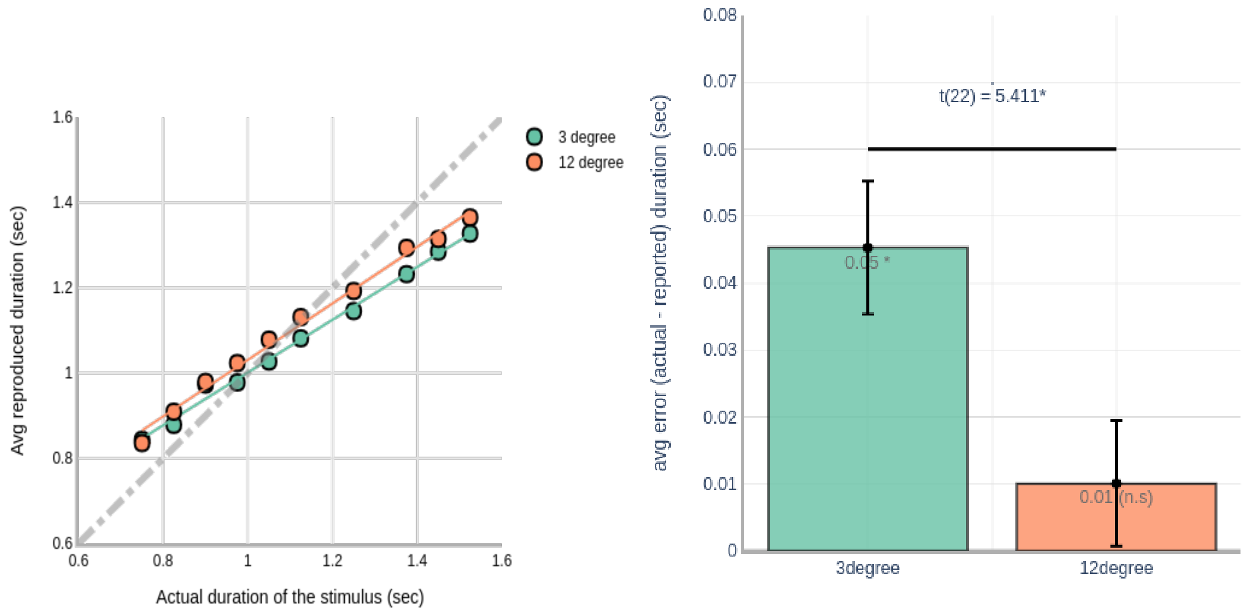

Figure 14 : Results from experiment 4

Results showing a) Fit linear models for the data illustrating the difference between 3 degree and 12 degree fits. b) Average error (actual - reported) plotted for each of the objective durations. Positive errors imply participant judgments were under-reported.

3.5.3 Discussion

In this experiment, I measured how objective durations are perceived in the fovea compared to the periphery. Overall participants seem to have overreported judgments for smaller durations (<= 1sec), and underreported the durations for larger durations. I will discuss more on this later. Furthermore, our results indicate that there is a significant difference in participant reports for how long the discs lasted in the fovea vs. periphery. Specifically, participant reports for the peripheral discs were more accurate (i.e., closer to the objective duration) while the foveal discs were under-reported. Why might participants be under-reporting the durations for the foveal discs? One explanation has to do with the differences in attention between the fovea and the periphery. It has been shown that attention distorts duration judgments (Eagleman & Pariyadath, 2009; Pariyadath & Eagleman, 2007, 2008, 2012; Tse, Intriligator, Rivest, & Cavanagh, 2004). In these studies, oddball stimuli which are more attention demanding are reported to last longer compared to standard stimuli. An information accumulation account predicts that subjective duration judgments are influenced by the amount of information accumulated during the corresponding event (Block & Reed, 1978; Brown, 1995; Poynter, 1989). In the case of oddballs, the amount of information accumulated over a period of time is higher compared to the regular standard discs. Thus causing the subjective duration expansion effect for oddballs. Chapter 04 discusses the perception of duration and the effects attention and memory have on duration judgments in much greater detail.

Further, (Carrasco et al., 2003) have shown that the temporal information sampling rate is higher in the periphery compared to the fovea. This could imply that more temporal information is accumulated in the periphery compared to the fovea. Then according to the change accumulation account, duration judgments in the periphery would be judged longer than those in the fovea since the periphery could accumulate more information over time compared to the fovea.

Alternatively, it is also possible that the rewards accumulated during the task might have differentially affected participant judgments in this task. Participants were rewarded at the end of each trial up to 10 points (maximum) depending on how accurate their reproduced durations were. It is possible that in an attempt to earn more points, participant reports might be manifesting some kind of bias that led to over reproduction at smaller duration intervals, and under reproduction at larger duration intervals. However, the reasons for the differential effects of reward in the periphery and the fovea are unclear at this time. This sets up a potential path for future studies to investigate more on the differential effects of rewards in foveal vs. peripheral duration judgments. In summary, this experiment further demonstrates the temporal processing differences between the fovea and the periphery.

3.6 General discussion:

Across three experiments, I manipulated the location of the cue across the horizontal axis in the visual field to probe which letters from the stream enter our awareness simultaneously as a function of visual eccentricity. I hypothesized that peripheral cues will result in reports of letters from the past compared to foveal cues. Accordingly the results from Experiments 1 and 2 showed that participants reported more letters from the past in the RSVP stream when the cue appeared in the periphery compared to the fovea. These results cannot be explained by shifts in attention and gaze (Posner, 1980) which would predict the opposite results, i.e., peripheral cues to be reported as simultaneous with future letters in the RSVP stream. Additionally, prior entry (Spence & Parise, 2010) also does not explain these results. Prior entry is a phenomenon which postulates that attended items enter our awareness earlier than unattended items. This would imply that, if participants are attending to the letter stream, the letters should enter our awareness earlier than the cue thus causing the unattended peripheral cue to be reported with a letter from the future. This is in direct contrast with the results that we observed. Furthermore, the results of Experiment 3 rule out the possibility that the distance between the cue and the letter stream is driving our results by dissociating distance from eccentricity. Finally, Experiment 4 measured the absolute durations at fovea and periphery and found that duration reproductions in the periphery are closer to the objective duration while participants under-reproduced durations of the discs presented in the fovea. One possible explanation for the differences in duration reproductions appeals to change accumulation theory which postulates that the amount of information accumulated over time might influence the duration of the event. Collectively, these results demonstrate significant differences in processing in the fovea and periphery.

The implications of the differential temporal processing between fovea and periphery has been often attributed to the non-uniform density of photoreceptors. For example, (Carrasco et al., 2003) have shown that temporal processing is faster in peripheral vision compared to the fovea. Additionally, early studies on temporal order judgments further highlight the difference in processing between fovea and periphery. In these paradigms, participants were presented with two discs appearing at fovea and periphery at various SOAs while fixating the screen center, and were asked to report the order of the discs (Rutschmann, 1966; Sekuler, Tynan, & Levinson, 1973; Stelmach & Herdman, 1991). For example, Rutschmann, 1966 has shown that peripheral discs need to be presented 50-60 msec earlier in order for participants to report both the foveal and peripheral discs as simultaneous.

However, we can see at least two caveats with these kinds of paradigms. Firstly, the results in these studies can be confounded by shifts in attention to the peripheral discs. Indeed, temporal order judgements have been shown to be influenced by factors such as directed attention (Stelmach & Herdman, 1991; S Sternberg et al., 1971; Saul Sternberg et al., 1973), task specific biases (Frey, 1990; Jaśkowski, 1993). For example, (Stelmach & Herdman, 1991) have shown that attending to one of the two discs speeds up processing in that location thereby affecting temporal order judgments. Secondly, the judgments in temporal order tasks have been subject to various task specific biases as discussed in Chapter 02. For example, (Jaśkowski, 1993) has shown that judgments for temporal order are affected when participants are given a ternary choice in addition to reporting whether one disc appeared first / second. Additionally, (Frey, 1990) has shown that the responses were affected when participants were asked to report which stimulus appeared first vs which stimulus appeared second highlighting the effect instructions have on these tasks.

The experiments presented in our studies isolate attention and task related effects in attempting to understand the differences in temporal processing between the fovea and periphery. These results demonstrate that events in the periphery are processed earlier compared to the events in the fovea. Specifically, a moment in visual experience stitches together events that happened at various moments across the visual field. In the next chapter I will explore how many moments in our perception accumulate to give rise to the duration that we experience.

4

Atypical stimuli immediately expand remembered duration

4.1 Introduction

In the domain of perceiving temporal properties a phenomenon known as ‘subjective expansion’ is among the most interesting and puzzling. The laboratory phenomenon involves asking people to estimate the duration of expected compared to unexpected stimuli, with unexpected stimuli reported as lasting longer (Tse et al., 2004). Laboratory studies build upon the common intuition that in stressful, important, or otherwise unexpected circumstances time can seem to slow down. Indeed, the phenomenon has a clinical name: Tachypsychia. Related folk notions suggest that perceived time can also speed up, ‘when having fun’ for example, or in a state of ‘flow’ (For example: Csikszentmihalyi & Csikzentmihaly, 1990) (However, I will focus entirely on expansion in the current report.)

How exactly the intuition that perceived time can expand translates into a mechanism remains mysterious. Two broader and prominent accounts of time perception have sought to incorporate the possibility of expansion. These are a pacemaker model (Creelman, 1962; Thomas & Weaver, 1975; Treisman, 1963; Treisman, Faulkner, Naish, & Brogan, 1990), and a change accumulation account

(Block & Reed, 1978; Brown, 1995; Matthews, 2011; Poynter, 1989). Pacemaker models advocate for the existence of an internal clock that measures time through regular discharges of some form, while the change accumulation account posits that time is perceived indirectly, by measuring the accumulation of some variety or varieties of information over time. Support for the latter model includes that paying attention to stimuli expands duration judgments, as though the accumulation of information about the stimulus or the dispatching of increased attention (or both) form the basis for a duration estimate (Creelman, 1962; Thomas & Weaver, 1975; Treisman, 1963). Pacemaker accounts incorporate the same results by suggesting that lapses in attention could result in missed discharges. Both kinds of prominent models therefore share a view in which distortions of perceived duration are possible, and both allow that attention might play a role in any distortions that take place.

Motivated by the common intuition that the rate of perceived time can vary, and by the room for this possibility in the primary models of time keeping, researchers over the last two decades have sought methods for producing duration distortions in the lab, especially by manipulating attention. A typical laboratory method for studying subjective distortions in duration is the oddball paradigm - where participants are presented with a sequence of standard and oddball stimuli, and asked to make duration judgments of the same. A seminal paper by Tse and colleagues (Tse et al., 2004) has become among the most highly cited examples, in part owing to its straightforward and replicable design. The logic in that paper was that visual attention tends to be engaged by atypical stimuli. Tse and colleagues reasoned that when asked to judge the duration of an object that is an ‘oddball’ relative to most of the objects seen in a sequence, that participants would overestimate. Participants in their experiments saw a sequence of repeating visual stimuli (usually about 7-13 black discs) that appeared on the screen. An oddball (e.g. a looming disc) was embedded within the sequence of repeating standards, and participants were instructed to judge the duration of the oddball (whether it was longer / shorter than the standards). Using a variety of report measures, Tse and colleagues found that, as predicted, participants reported that the oddballs lasted longer than their standard counterparts of the same objective duration.

A variety of experiments have followed up on these results, documenting properties that can make an object an 'oddball,' as well as properties that interact with duration estimation in these paradigms (e.g. Alexander Varakin, Klemes, & Porter, 2013; Cicchini & Morrone, 2009; Hays, Klemes, & Varakin, 2016; Herbst, Javadi, van der Meer, & Busch, 2013; Johnston, Arnold, & Nishida, 2006; R. Kanai & Watanabe, 2006; Matthews, 2011; Palumbo, Ogden, Makin, & Bertamini, 2014; Roseboom et al., 2019; Seifried & Ulrich, 2011; Yeshurun & Marom, 2008). Similarly, these specific results are cited by both sides in the debate between pacemaker and information accumulation accounts of timekeeping, as well as by other theories. However, these theories are not the target of interest currently. Instead, I sought to interrogate an assumption that is shared by nearly all extant accounts of expansion effects: that the effects are perceptual in the first place.

What I mean by perceptual in this context is 'ongoing'. Perceptual effect here refers to the idea that it is an effect on the way the stimulus is first represented in the stream of consciousness, or put differently: the primary product of perceptual processing as opposed to a subsequent / secondary encoding of the event. The question, therefore, is whether being an oddball causes a change in the ongoing perceptual processing of a stimulus. The alternative is that the observed effects are retrospective, what we would deem a distortion in the immediate memory representation of an object and its duration. While the possibility that expansion effects might be memory-driven has been suggested occasionally, it has rarely been tested directly. Moreover, the few experiments that have attempted to document an ongoing perceptual effect when time expands have failed to find evidence. A notable example is a study by Stetson & colleagues (Stetson, Fiesta, & Eagleman, 2007). Two features make their experiment stand out: (1) They reasoned that time is most severely distorted during actual and severe stress. They therefore conducted their experiment on volunteers during the free fall portion of a bungee jump. (2) They theorized that the ongoing experience of time slowing down should manifest in a faster processing speed for incoming stimuli. By analogy to a car accident, the idea is that time slowing down amounts to a person running their computational clock ‘hot,’ processing much more than they normally would during such a short actual duration. The researchers therefore built a hand-affixed device to present visual stimuli serially, and thereby to test the ‘frame rate’ of visual processing during free fall. Unfortunately, no difference was found between free-fall and grounded processing.

Absence of evidence is not evidence of absence, however, and the prevailing view seems to be that expansion effects are a perceptual phenomenon, time seeming to slow down in the presence of a stimulus or during an experience, as opposed to a memory phenomenon, time seeming to have lasted a long time upon immediate reflection. Of course, accounts of time slowing down demand a clear specification of what is meant. No matter how engaging or not, a 90 minute long movie takes 90 minutes to watch. Likewise, a 30 second long car accident unfolds over 30 seconds, regardless of how victims experience it. So what does it mean to report something as lasting longer than another event of objectively equal duration?

I hypothesized that expanded time estimates primarily reflect a memory mechanism, not an online or ongoing perceptual mechanism during the experience which is then remembered as expanded. To test this hypothesis I applied a small but novel change to one of the methods of duration estimation employed by Tse and colleagues (Tse et al., 2004). I also replicated their effects with the original methods. I argue that my variant of the task more clearly probes an observer's ongoing processing of an oddball stimulus, while the more typical methods probe immediate memory. The presence of an oddball effect with their methods therefore reflects an effect in memory. The absence of an effect with our changed version reveals the lack of an ongoing, perceptual effect.

4.2 Experiment 1: Replication of Tse and colleagues (2004)

I sought to replicate the well-known temporal expansion effect reported in the literature using the oddball paradigm. In the current experiments, I manipulated the probability with which oddball stimuli appeared in the duration judgment task. Participants viewed a sequence of discs that were displayed on the computer screen for a given duration. The task was to report the duration of the last stimulus seen by pressing and holding the spacebar. The last stimulus was either a ‘standard’ stimulus (a black disc) like the others that preceded in the trial, or an ‘oddball,’ a disc with changing or different properties. I theorize that this task measures remembered but not necessarily perceived duration, owing to the retrospective nature of the response, which follows the relevant oddball stimulus. The schematic of the experiment design is illustrated in the Figure 15.

4.2.1 Methods

Participants

20 Johns Hopkins undergraduates participated for course related credit. All reported normal or corrected-to-normal vision. The protocol was approved by the Homewood Institutional Review Board (HIRB). Per standard practice in this lab, all results were immediately deidentified. Demographic data were collected separately and cannot be tracked directly to this or any experiments in the lab.

Materials:

I used an iMac (Retina 5K, Late 2015, Apple Inc, Cupertino, California), and Psychopy3 software to test the participants. Stimuli were presented on a 27 inch display with a refresh rate of 60 Hz (16.667 msec per frame). Participants were seated approximately 55 cm away from the monitor, and the display spanned about [46 x 29] degree visual angle.

Participants initiated a trial by keypress, at which point a black disc (size 1.06 deg diameter) appeared in the center of the display, remaining in place for one of the 10 durations included below. A participant saw four disks that appeared and disappeared sequentially with an inter stimulus interval (ISI) of 1 second. They had to report the duration of the last seen disc by pressing and holding the spacebar. Throughout the experiment there were three types of stimuli used. These three stimuli can be put into two categories: One was a standard stimulus (a black disc of diameter 1.06 degree visual angle), and the other was an oddball stimulus. The oddball stimulus could either be a disk of a different color (blue), or a looming disk that increased in size (minimum size: 0.53 degree diameter; maximum size: 1.06 degree diameter) at a constant rate for the given duration. All the stimuli were presented on a white background. In a given trial, all the disks lasted for the same duration. We used ten different durations ranging from 750 to 1525 msec - [750, 825, 900, 975, 1050, 1125, 1250, 1375, 1450, 1525] msec. There were a total of 100 trials, 10 for each duration condition. The 10 trials for each duration condition contained a mix of oddball and standard trials, i.e., the last disc was either an oddball or a standard. Due to a technical glitch, participants saw (6 standards, 2 color odd balls, 2 looming oddballs = Total 10 trials) for alternative durations (i.e., 750, 900, 1050, … msec), and (4 standards, 3 color oddballs, 3 looming oddballs = Total 10 trials) for the remaining durations (i.e., 825, 975, 1125, … msec). All the participants had the same design as mentioned. The order of the durations and stimulus conditions in each trial was randomized.

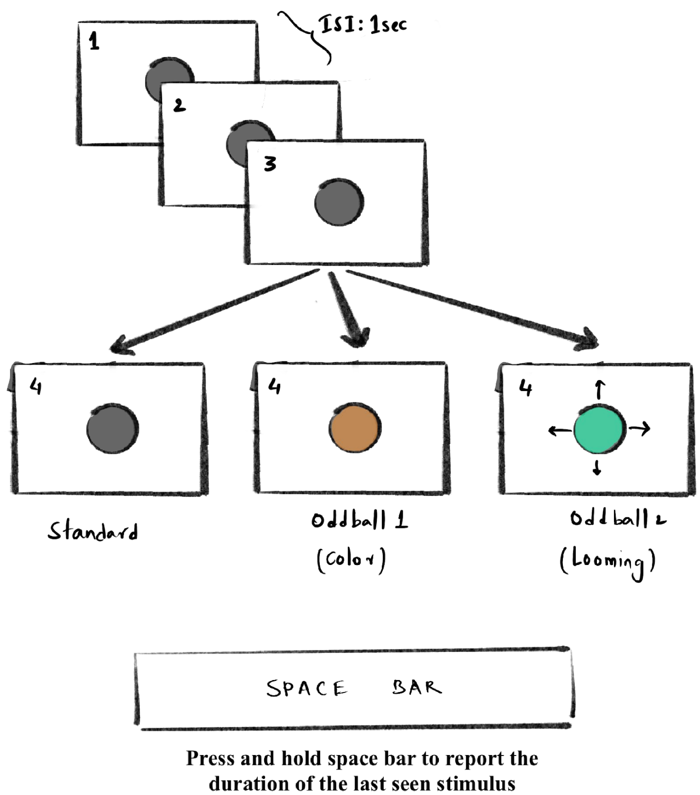

Figure 15 : Design of subjective time expansion experiment – conceptual replication of (Tse et al., 2004)

In a given trial participants saw a sequence of 4 discs. The first three of them were always a standard disc, the fourth disc was an oddball of different color, or an oddball that loomed, or a standard disc. Participants reproduced the duration of the last seen disc by pressing and holding the space bar.

Procedure:

Participants performed a total of 100 trials each so that the experiment lasted for an average of 20-30 minutes. They were told that they would be playing a game in which they would be seeing four discs in any given trial, and would have to report the duration of the last seen disc. Participants reported the duration by pressing and holding the space bar for however long they thought the fourth disc lasted. They were instructed to be as accurate as possible in reproducing the duration. This was enforced by awarding them points in each trial. Each trial was for 10 points, and the experiment was for a total of 1000 points. They were told that their course credit would be doubled if they scored 650/1000 points, although everyone received double the course credit for participation. No points were awarded in a trial if they went over the duration, but the reproduced duration was recorded.

4.2.2 Results:

For each participant, I collected the reproduced duration of each stimulus type in a given trial. The data were subject to an ANOVA test with reproduced duration as the dependent variable, and objective duration, and stimulus condition as predictor variables. I found a significant main effect of stimulus condition ($F(2, 1996) = 52.47$, $p < 0.0001$), and duration ($F(1, 1996) = 1168.52$, $p < 0.0001$). The interactions between duration and stimulus conditions were not significant. Further, planned contrasts revealed that experiencing any one condition of oddball significantly increased participant reports compared to the standard condition $t(1996) = 2.15$, $p = 0.03$ (one-tailed), and that looming oddballs were perceived as longer than the colored oddballs $t(1996) = 9.31$, $p < 0.001$ (one-tailed). Together these results suggest that the stimulus condition had an effect on the duration reproduction task. Specifically, oddballs were reproduced longer than the standard stimuli for the same objective duration as can be seen from Table 1.

	Estimate	*Std. Error*	*tvalue*	*Pr*($ > $$|$*t*$|$)
(*Intercept*)	0.1640	0.0208	7.88	0.0000
*Stimulus_condition*1	0.0240	0.0111	2.15	0.0313
*Stimulus_condition*2	0.1035	0.0111	9.31	0.0000
Duration	0.6075	0.0178	34.18	0.0000

	Df	*SumSq*	*MeanSq*	*Fvalue*	*Pr*($ > $*F*)
Stimulus_condition	2	4.32	2.16	52.47	0.0000
Duration	1	48.15	48.15	1168.52	0.0000
Residuals	1996	82.24	0.04		

Table 1 : ANOVA and Linear Model results for experiment 1 – subjective time expansion

Output of the linear regression model with reproduced duration as the dependent variable, and duration and stimulus condition (categorical) as predictor variables, and the F-statistic computed using ANOVA

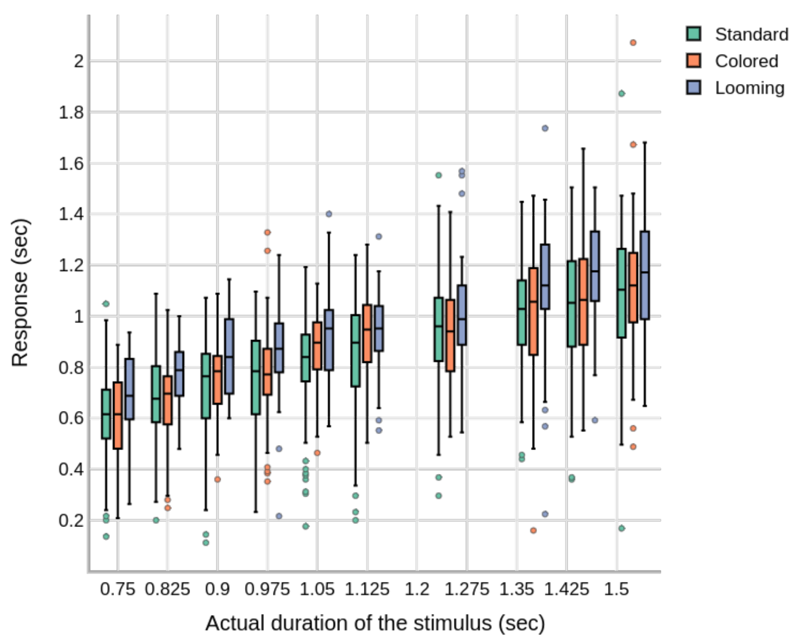

Figure 16 : Raw response data for experiment 1 (replication of Tse et al., 2004)

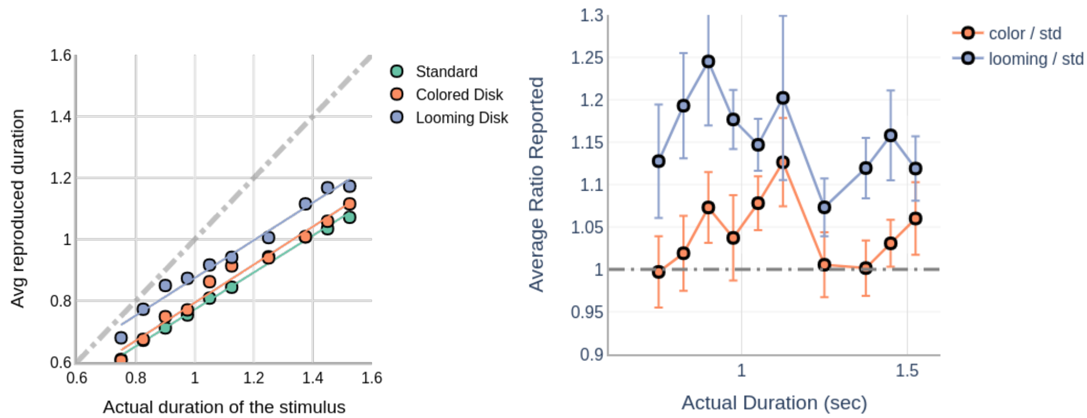

Figure 17 : Results for experiment 1 (replication of Tse et al., 2004)

a) Results of the fitted linear model for each of the conditions b) An alternative way of plotting the results using ratio. Y axis measures the average ratio of oddball and standard responses for each of the duration conditions. A ratio > 1 would imply an expansion effect for the oddballs, and a ratio < 1 would imply a contraction effect for the oddballs. Error bars indicate the 95% CI.

4.2.3 Discussion:

I investigated subjective distortions of time in the oddball paradigm. I observed that the durations for both standards and oddballs alike were underestimated (as can be seen from Figure 16 and Figure 17). A primary reason for this under reporting behavior is likely to do with the instructions presented to the participants. Participants were told that each trial would result in a specific reward, and that going over the actual duration would not yield them any reward points in that trial. In spite of this manipulation we were able to replicate the classic finding that the durations for the oddball stimuli are perceived as longer than the repetitive standard stimuli (Birngruber, Schröter, & Ulrich, 2015; Cai, Eagleman, & Ma, 2015; Eagleman & Pariyadath, 2009; Matthews, 2011; New & Scholl, 2009; Pariyadath & Eagleman, 2007; Tse et al., 2004). Specifically, I observed that the looming oddballs were reported to last longer than the colored oddballs followed by the standards of the same duration.

Why did the colored oddballs have a smaller effect compared to their looming counterparts? One potential explanation concerns the change accumulation account. Change accumulation accounts posit that subjective distortions of duration for oddballs is driven by the amount of change in information that takes place over that duration (Block & Reed, 1978; Brown, 1995; Poynter, 1989). Colored stimuli in our experiments have a transient change of color in the beginning compared to the oddballs which constantly loomed with time, potentially accumulating information change over time. In other words, whilst different from the standards, colored oddballs do not change during their presentation other than that one time where they change color momentarily. In line with this hypothesis, it is possible that the looming oddballs produce a higher effect compared to the color oddballs because of the greater amount of change in information for the looming oddballs.

Alternatively, it is also possible that the reward structure of the experiment might have influenced participant reports differentially. Subjective distortions have been ascribed to stimulus specific arousal (Ulrich, Nitschke, & Rammsayer, 2006). According to this arousal account, unexpected stimuli increase arousal and thus increase the speed of the internal clock that is used to measure time. So it is possible that the reports for the looming oddballs are differentially affected compared to the colored oddballs and the standards. However, whether change accumulation or differential rewards affect the way we experience time when we perceive oddballs / standards is not clear. It is possible that participant reports for these stimuli are driven by memory distortions and that change accumulation and/or differential rewards exclusively affect the way we remember duration. Experiment 1 does not distinguish between whether the distortions reported are a result of our experience or solely our memories.

I therefore investigated this question with a novel experimental design in Experiment 2. The logic of the experimental design was to probe participants' online experience of the oddballs. I did this by providing participants with a feedback stimulus as they reported durations. I will explain the logic behind this manipulation in detail in Experiment 2. But before we dive into Experiment 2, I sought to replicate the oddball effect once again with a slight variation that will be necessary for introducing the reasoning behind Experiment 2.

4.3 Experiment 1.1: Conceptual replication of Experiment 1

I replicated Experiment 1 with a slight modification. In this experiment, participants were provided with a visual stimulus as they reproduced the duration of the stimuli they last remembered in the trial sequence. Specifically, I wanted to know if providing visual stimulus to participants during reproductions significantly impacted their judgments as they reported the remembered durations. The only difference between this experiment and Experiment 1 was that when participants held down the spacebar to report retrospective duration, a standard black disc appeared on the screen, disappearing when the space bar was released. In the original experiment, and in that of Tse and colleagues, responses were made while viewing an empty screen. An illustration of the design can be found in Figure 18.

4.3.1 Methods

Participants

20 Johns Hopkins undergraduates participated for course related credit. All reported normal or corrected-to-normal vision. The protocol was approved by the Homewood Institutional Review Board (HIRB). Per standard practice in this lab, all results were immediately deidentified. Demographic data were collected separately and cannot be tracked directly to this or any experiments in the lab.

Materials:

The materials for this replication were the same as the previous experiment with a slight modification. Participants saw four discs sequentially. Just like Experiment 1, the fourth disc was either the standard disc, or an oddball (either color, or a looming disc). Participants were instructed to report the duration of the last disc they saw by pressing the spacebar. However, when they pressed the spacebar, a new disc (always a standard black disk of diameter 1.06 degree visual angle) appeared on the screen. This disc was designed to assist participants in reporting the duration of the last (4th) disc in the sequence. I used this experimental manipulation to see if presenting a visual stimulus during reproduction would change the way participants reported the durations for standards and oddballs.

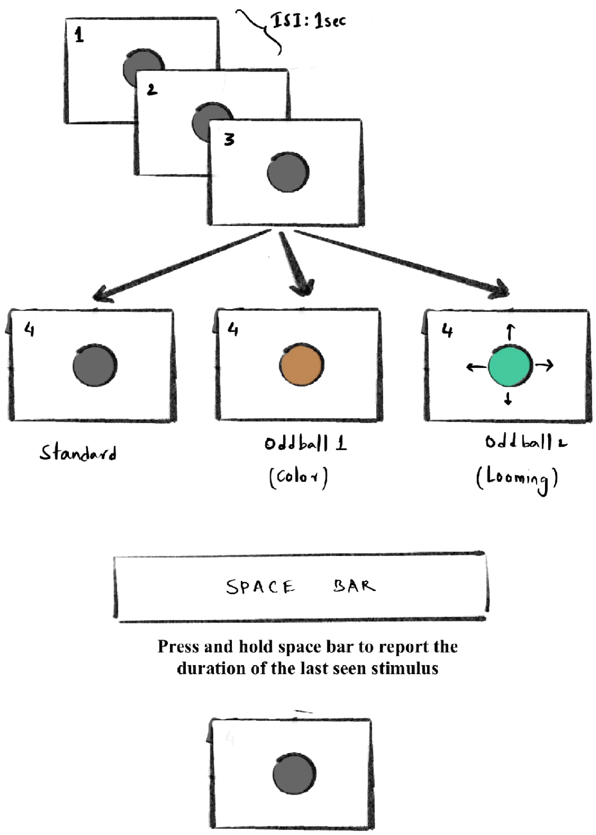

Figure 18 : Design of experiment 1.1 – subjective time expansion where a visual stimulus was provided during reproduction

In a given trial participants saw a sequence of 4 discs. The first three of them were always a standard disc, the fourth disc was an oddball of different color, or an oddball that loomed, or a standard disc. Participants reproduced the duration of the last seen disc by pressing and holding the space bar. When they pressed the space bar a new disc would appear on the screen for the duration of their reproduction. Participants had to let go off the spacebar to make the new disc disappear.

Procedure:

Participants performed a total of 100 trials each so that the experiment lasted for an average of 20-30 minutes. They were told that they would be playing a game where they would be seeing four discs in any given trial, and that they would have to report the duration of the last seen disc. Participants reported the duration by pressing and holding the space bar for however long they thought the fourth disc had lasted. They were told that when they press a spacebar, it would turn on a new disc. They had to let go of the spacebar to turn that disc off. Basically, the purpose of this disc was to help them prospectively judge the duration of the last disc they saw in a sequence. They were instructed to be as accurate as possible in reproducing the duration. This was enforced by awarding them points in each trial. Each trial was for 10 points, and the experiment was for a total of 1000 points. They were told that their course credit would be doubled if they scored 650/1000 points, although everyone received double the course credit for participation. No points were awarded in a trial if they went over the duration.

4.3.2 Results:

For each participant, I collected the reproduced duration of each stimulus type in a given trial. The data were subject to an ANOVA test with reproduced duration as the dependent variable, and objective duration, and stimulus condition as predictor variables. We found a significant main effect of stimulus condition ($F(2, 1996) = 111.97$, $p < 0.0001$), and duration ($F(1, 1996) = 1230.91$, $p < 0.0001$). The interactions between duration and stimulus conditions were not significant. Further, planned contrasts revealed that experiencing any one condition of oddball significantly increased participant reports compared to the standard condition $t(1996) = 2.47$, $p = 0.01$ (one-tailed), and that looming oddballs were perceived as longer than the colored oddballs $t(1996) = 13.92$, $p < 0.001$ (one-tailed) [See Table 2 for more details]. Together these results suggest that the stimulus condition had an effect on the duration reproduction task. Specifically, oddballs were reproduced longer than the standard stimuli for the same given objective duration as can be seen from Figure 19 and Figure 20 .

	Df	*SumSq*	*MeanSq*	*Fvalue*	*Pr*($ > $*F*)
Stimulus_condition	2	8.64	4.32	111.97	0.0000
Duration	1	47.49	47.49	1230.91	0.0000
Residuals	1996	77.01	0.04		

	Estimate	*Std. Error*	*tvalue*	*Pr*($ > $$|$*t*$|$)
(*Intercept*)	0.1348	0.0201	6.69	0.0000
*Stimulus_condition*1	0.0265	0.0108	2.47	0.0137
*Stimulus_condition*2	0.1498	0.0108	13.92	0.0000
Duration	0.6033	0.0172	35.08	0.0000

Table 2 : ANOVA and Linear Model results for experiment 1.1

Output of the linear regression model with reproduced duration as the dependent variable, and duration and stimulus condition (categorical) as predictor variables, and the F-statistic computed using ANOVA

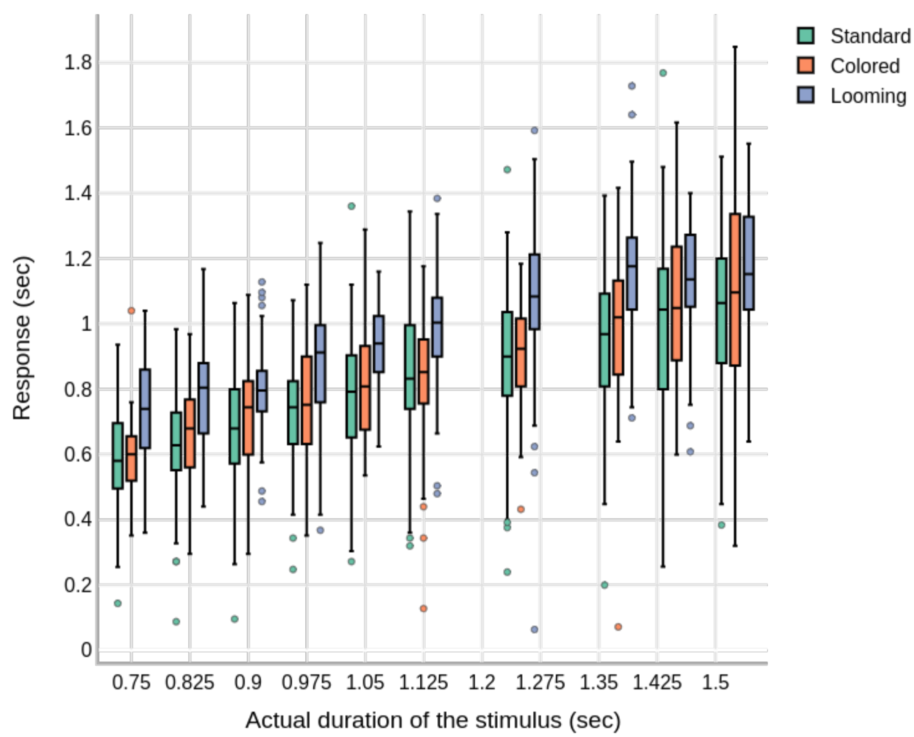

Figure 19 : Raw data for experiment 1.1 – duration judgments in the presence of a visual stimulus

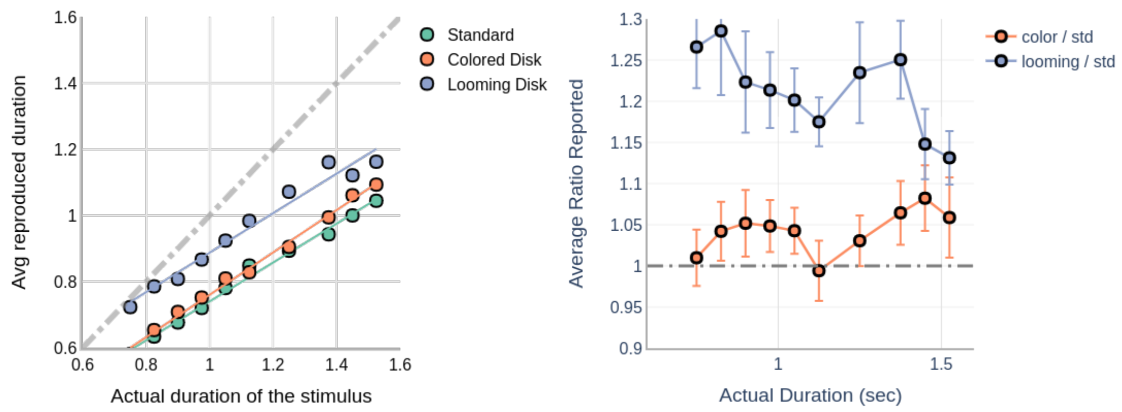

Figure 20 : Results for experiment 1.1 – duration judgments in the presence of a visual stimulus

a) results of the fitted model for each of the conditions c) An alternative way of plotting the results using ratio. Y axis measures the average ratio of oddball and standard responses for each of the duration conditions. A ratio > 1 would imply an expansion effect for the oddballs, and a ratio < 1 would imply a contraction effect for the oddballs. Error bars indicate the 95% CI.

4.3.3 Discussion:

I conceptually replicated the results of Experiment 1 - where participants performed an oddball duration judgment task by reproducing the duration through pressing and holding the spacebar on the keyboard. Just like in Experiment 1, participants under reported the durations of both oddball and standard stimuli. In spite of the reward structure and restricting participants from over reporting the durations, I was able to replicate expansion effects for both looming and colored oddballs (as can be seen from figure 4c). Similar to the results of Experiment 1, colored oddballs had lower expansion effects compared to the looming oddballs. The main purpose of this experimental replication was to see if providing participants with a visual stimulus during reproduction impacted the effects. It did not. Note that in this experiment, the results could also be interpreted as revealing a memory effect. Participants were asked to use the spacebar to onset and remove a black disc from the screen and to do so for the same duration of the last stimulus they saw in the presentation sequence, which could have been an oddball or a black standard.

4.4 Experiment 2: Online experience of time is not distorted

In this experiment, I manipulated the oddball paradigm to see whether time subjectively expands for oddball events in an ongoing, perceptual sense. Is each moment in the presence of the oddball a longer moment than it should be? Or is it only upon reflection that time spent viewing the oddball seems like a longer time than it should?

The task was identical to Experiment 1.1, except that here the last stimulus seen in the presentation sequence was always a black standard. In order to reproduce the duration of that standard, participants used the spacebar to onset and then remove a disc, which could be either another standard or an oddball. I reasoned that if the experience of an oddball is distorted in an ongoing way—if we perceive every moment with an oddball as longer than with a standard counterpart—duration judgments should be shorter, on average, when the reproduction initiated stimulus is an oddball. If each moment with the oddball feels longer than it should, then observers should feel like their reproduction is complete sooner than normal when staring at an oddball during the reproduction. The experiment design is illustrated in Figure 21.

4.4.1 Methods

Participants

22 Johns Hopkins undergraduates took part in this study for course related credit. All the participants had normal / corrected-to-normal vision. All the study

procedures were approved, and conducted in compliance with the guidelines provided by the Homewood Institutional Review Board (HIRB).

Materials:

I used an iMac (Retina 5K, Late 2015, Apple Inc, Cupertino, California), and Psychopy3 software to test the participants. Stimuli were presented on a 27 inch display with a refresh rate of 60 Hz (16.667 msec per frame). Participants were seated approximately 55 cm away from the monitor, and the display spanned about [46 x 29] degree visual angle. In each trial, a participant saw three disks that appeared and disappeared sequentially with an inter stimulus interval (ISI) of 1 second. They had to report the duration of the last seen disc by pressing and holding the space bar. However, when they pressed the spacebar to reproduce the duration, they were presented with a feedback disc (either a standard disc or an oddball — see below) to help them judge the duration of the last stimulus. Throughout the experiment there were three types of feedback stimuli used. These three feedback stimuli can be put into two categories: One was a standard stimulus (a black disk of diameter 1.06 degree visual angle), and the other was an oddball stimulus. The oddball stimulus could either be a disk of a different color (blue), or a looming disk that increased in size (minimum size: 0.53 degree diameter; maximum size: 1.06 degree diameter) at a constant rate for the given duration. All the stimuli were presented on a white background. In a given trial, all the disks lasted for the same duration. I used ten different durations ranging from 750 to 1525 msec - [750, 825, 900, 975, 1050, 1125, 1250, 1375, 1450, 1525] msec. There were a total of 120 trials, 12 for each duration condition. The 12 trials for each duration condition contained a mix of oddball and standard trials, i.e., the last disc was either an oddball or a standard. Participants saw (6 standards, 3 color oddballs, 3 looming oddballs = Total 12 trials) per duration. All the participants had the same design as mentioned. The order of the durations and stimulus conditions in each trial was randomized.

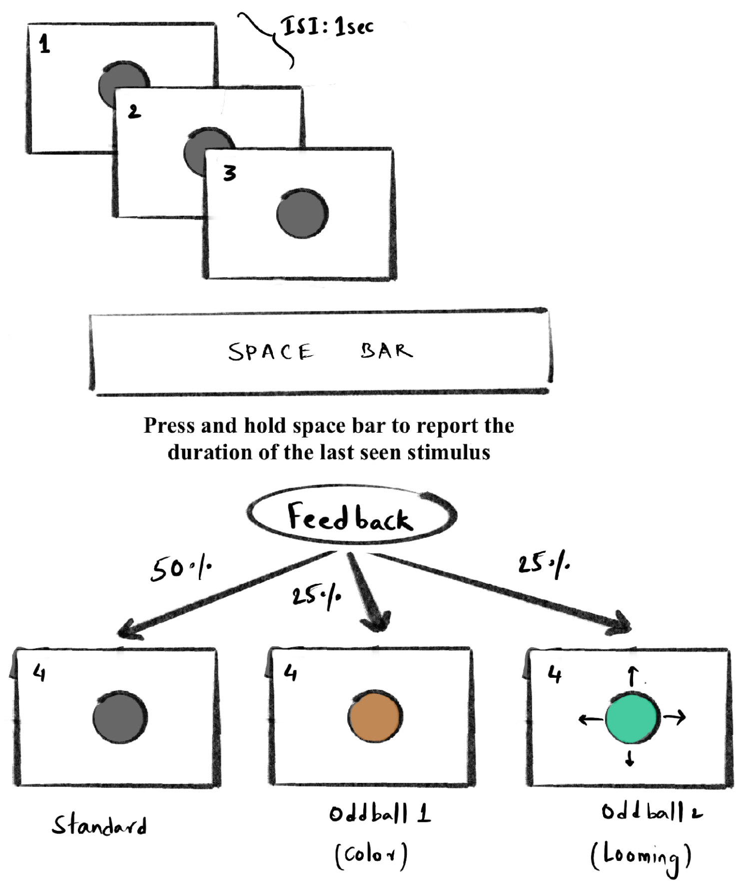

Figure 21 : Design for experiment 2 – online experience

In a given trial participants saw a sequence of 4 discs. The first three of them were always a standard disc, the fourth disc was an oddball of different color, or an oddball that loomed, or a standard disc. Participants reproduced the duration of the last seen disc by pressing and holding the space bar.

Procedure:

Participants performed a total of 120 trials each so that the experiment lasted for an average of 20-30 minutes. They were told that they would be playing a game where they would be seeing four discs in any given trial, and that they would have to report the duration of the last seen disc. Participants reported the duration by pressing and holding the space bar for however long they thought the fourth disc had lasted. They were told that when they pressed the spacebar, it would turn on another disc on the screen. They could use this feedback disc to judge the duration of the last disc in the sequence. They would need to let go of the spacebar to turn the disc off. They were instructed to be as accurate as possible in reproducing the duration. This was enforced by awarding them points in each trial. Each trial was for 10 points, and the experiment was for a total of 1200 points. They were told that their course credit would be doubled if they scored 750/1200 points, although everyone received double the course credit for participation. No points were awarded in a trial if they went over the duration.

4.4.2 Results:

For each participant, I have collected the reproduced duration of each stimulus type in a given trial. The data were subject to an ANOVA test with reproduced duration as the dependent variable, and objective duration, and stimulus condition as predictor variables. I found a significant main effect of duration ($F(1, 2636) = 1970.71$, $p < 0.0001$), but not the stimulus condition used as feedback ($F(2, 2636) = 0.74$, $p = 0.47$). The interactions between duration and stimulus conditions were not significant. Further, planned contrasts revealed that neither the colored nor the looming oddballs significantly increased participant reports compared to the standard condition t(2636) = -0.14, p = 0.88 (one-tailed), t(2636) = 1.09, p = 0.27 (one-tailed) [See Table 3 for more details]. I further confirmed the validity of these results by computing the Bayes factor. I computed the BIC scores for two models: a model with both stimulus condition and duration as predictor variables (aka full model — where stimulus condition matters), and another model with just the duration as the predictor variable (null model — where stimulus condition does not matter). The Bayes factor analysis comparing the full model vs null model revealed a BF = 0.007 decisively suggesting that the observed evidence favors the null model where the stimulus condition in the feedback condition did not matter in duration reproduction. Together these results suggest that the stimulus condition had no effect on the duration reproduction task as can be seen from Figure 22 and Figure 23.

	Df	*SumSq*	*MeanSq*	*Fvalue*	*Pr*($ > $*F*)
Stimulus_condition	2	0.05	0.02	0.74	0.4780
Duration	1	61.49	61.49	1970.71	0.0000
Residuals	2636	82.25	0.03		

	Estimate	*Std. Error*	*tvalue*	*Pr*($ > $$|$*t*$|$)
(*Intercept*)	0.2162	0.0159	13.63	0.0000
*Stimulus_condition*1	−0.0012	0.0084	−0.14	0.8874
*Stimulus_condition*2	0.0092	0.0084	1.09	0.2755
Duration	0.5972	0.0135	44.39	0.0000

Table 3 : ANOVA and Linear Model results for experiment 2 – online experience

Output of the linear regression model with reproduced duration as the dependent variable, and duration and stimulus condition (categorical) as predictor variables, and the F-statistic computed using ANOVA.

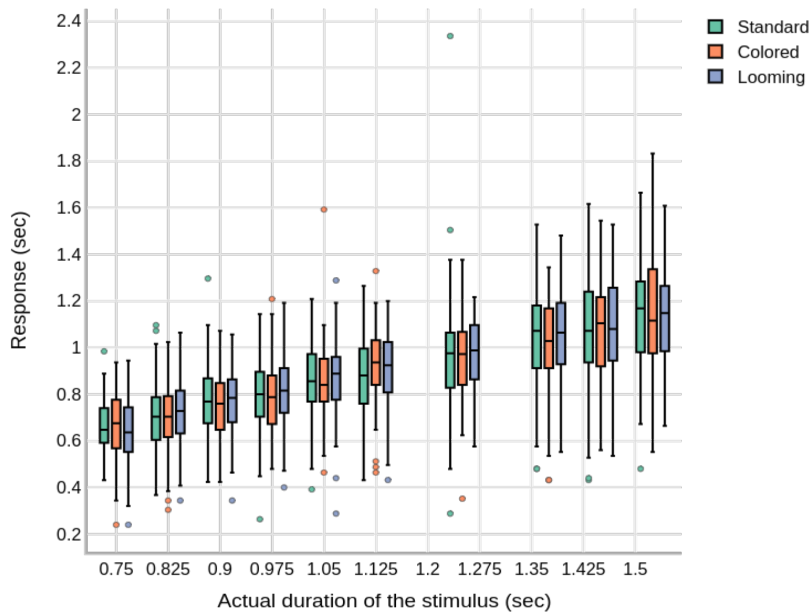

Figure 22 : Raw data for experiment 2 – online experience

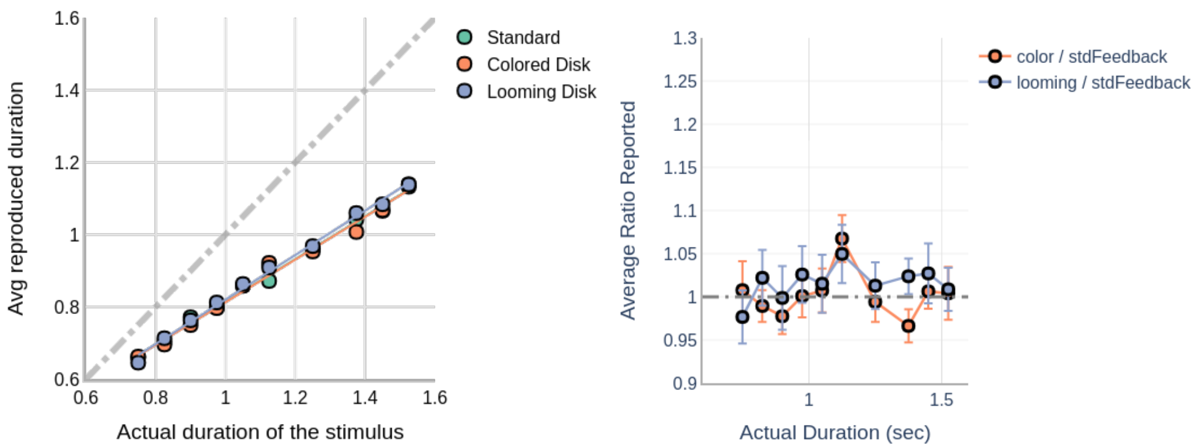

Figure 23 : Results from experiment 2 – online experience

a) results of the fitted model for each of the conditions b) An alternative way of plotting the results using ratio. Y axis measures the average ratio of oddball and standard responses for each of the duration conditions. A ratio > 1 would imply an expansion effect for the oddballs, and a ratio < 1 would imply a contraction effect for the oddballs. Error bars indicate the 95% CI.

4.4.3 Discussion:

In this experiment, I investigated whether every moment of our oddball experience is distorted compared to the standard stimulus. Participants watched a sequence of 3 discs which were always standards, and were instructed to report the duration of the last disc. When they pressed the spacebar to report the duration, this turned on a feedback stimulus which was either an oddball, or a standard. I hypothesized that if every moment in our experience of oddballs is distorted, then we should observe significant differences in duration reproductions for different feedback categories. Specifically, if every moment of the oddball is expanded, it would lead to shorter reproductions for oddball feedback stimuli compared to the standards. Overall, participants under reported the objective duration of the stimuli - a trend we observed in the previous experiments as well. However, I did not find any significant differences in duration reports between oddballs and the standards. Earlier experiments highlighted the impact of oddballs either through a change accumulation account (Block & Reed, 1978; Brown, 1995; Poynter, 1989), or through arousal (Ulrich et al., 2006) that might have resulted in the distortions of reported durations. However, they could not determine whether these mechanisms impact the way we experience oddballs or if the distortions are a result of the way we remember the durations of the oddballs. Experiment 2 was designed to probe our online experience of oddballs and standards. The lack of differences in reports in Experiment 2 coupled with the results of Experiments 1 and 1.1 suggests that our experience of duration is not distorted when we experience oddballs and standards. Rather, the way we remember these durations is distorted. I wanted to test how robust these results are. So I replicated the experiment online with a greater number of participants. Details mentioned below.

4.5 Experiment 2.1 - Online replication of Experiment 2

4.5.1 Method

Participants

145 Johns Hopkins undergraduates took part in this study on an online platform (www.sona-systems.com) for course related credit. All the participants had normal / corrected-to-normal vision. All the study procedures were approved, and conducted in compliance with the guidelines provided by the Homewood Institutional Review Board (HIRB).

Materials and procedure:

The materials and procedure for the online replication were the same as the in lab study discussed earlier. I used html and JavaScript to replicate the experimental design for this online study. A demonstration of this experiment can be found here (http://www.au.perceptionresearch.org/Exp2gameOnTP/Tachypsychia-experiment2.html?workerId=3769)

4.5.2 Results:

There were a total of 145 participants in this experiment. Since this was an online replication, I had to do some data cleaning. Depending on how long the participants took to finish the experiment, I filtered out participants who took longer than 50 minutes to perform the experiment. Additionally, since the maximum duration of the stimulus was 1500 msec, I also filtered out subjects whose reproduced durations were greater than

2000 msec. This meant that there were a total of 122 participants in our experiments. For each participant, I collected the reproduced duration of each stimulus type in a given trial. The data were subject to an ANOVA test with reproduced duration as the dependent variable, and objective duration, and stimulus condition as predictor variables. I found a significant main effect of duration ($F(1, 14996) = 6147.85$, $p < 0.0001$), but not the stimulus condition used as feedback ($F(2, 14996) = 0.14$, $p = 0.83$). The interactions between duration and stimulus conditions were not significant. Further, planned contrasts revealed that neither the colored nor the looming oddballs significantly increased participant reports compared to the standard condition $t(14996) = -0.53$, $p = 0.59$ (one-tailed), $t(14996) = -0.21$, $p = 0.83$ (one-tailed) [See Table 4 for more details]. I further confirmed the validity of these results by computing the Bayes factor. I computed the BIC scores for two models: a model with both stimulus condition and duration as predictor variables (aka full model — where stimulus condition matters), and another model with just the duration as the predictor variable (null model — where stimulus condition does not matter). The Bayes factor analysis comparing the full model vs null model revealed a BF = 0.000073 decisively suggesting that the observed evidence favors the null model where the stimulus condition in the feedback condition did not matter in duration reproduction. Together these results suggest that the stimulus condition had no effect on the duration reproduction task as can be seen from Figure 24 and Figure 25.

	Df	*SumSq*	*MeanSq*	*Fvalue*	*Pr*($ > $*F*)
Stimulus_condition	2	0.01	0.00	0.14	0.8673
duration	1	210.93	210.93	6147.85	0.0000
Residuals	14996	514.51	0.03		

	Estimate	*Std. Error*	*tvalue*	*Pr*($ > $$|$*t*$|$)
(*Intercept*)	0.3675	0.0070	52.65	0.0000
Stimulus_condition[1]	−0.0020	0.0037	−0.53	0.5942
Stimulus_condition[2]	−0.0008	0.0037	−0.21	0.8373
duration	0.4640	0.0059	78.41	0.0000

Table 4 : ANOVA and Linear model results for experiment 2.1 – replication of online experience

Output of the linear regression model with reproduced duration as the dependent variable, and duration and stimulus condition (categorical) as predictor variables, and the F-statistic computed using ANOVA.

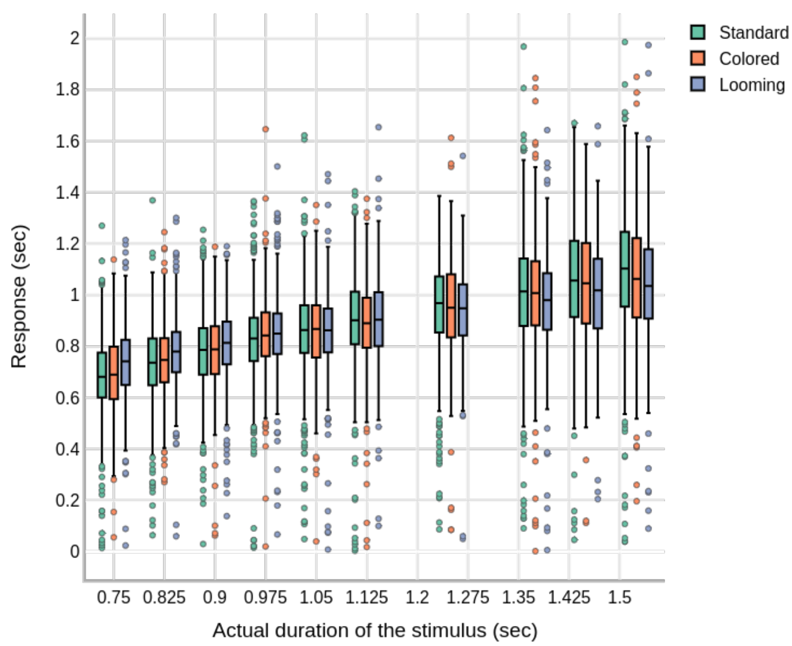

Figure 24 : Raw data for experiment 2.1 – replication of online experience

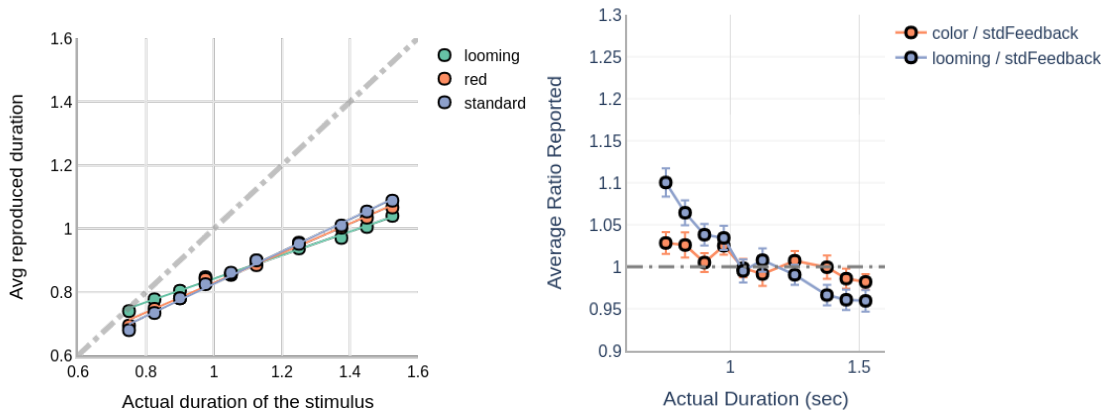

Figure 25 : Results for experiment 2.1 – replication of online experience

a) results of the fitted model for each of the conditions b) An alternative way of plotting the results using ratio. Y axis measures the average ratio of oddball and standard responses for each of the duration conditions. A ratio > 1 would imply an expansion effect for the oddballs, and a ratio < 1 would imply a contraction effect for the oddballs. Error bars indicate the 95% CI.

4.6 General discussion

I investigated whether the phenomenon of subjective time expansion happens in our perceptual experience in this paper. Across four experiments I was able to isolate memory and perceptual effects when we experience oddball events. I did this by first investigating oddball effects using existing methodologies that have obvious memory confounds. I then used a novel experimental manipulation by providing participants with feedback as they reproduced the remembered duration. This manipulation allowed me to tap directly into the experience of oddballs and standards as we perceive them. In particular, Experiment 1 replicated the temporal expansion effects associated with oddballs (Eagleman & Pariyadath, 2009; New & Scholl, 2009; Pariyadath & Eagleman, 2007, 2008, 2012; Tse et al., 2004; van Wassenhove, Buonomano, Shimojo, & Shams, 2008). Experiment 1.1 investigated whether the presence of a feedback stimulus would significantly impact how we remember the duration of the oddballs. The results from this experiment suggested that the presence of feedback did not significantly affect the observed results. Participants reported the duration of the oddballs as subjectively lasting longer than the standards, and the effect sizes we observed were similar to those of Experiment 1. Finally, Experiments 2 and 2.1 isolated the perceptual and memory components of the oddball effect by having participants report the duration of the standard disc while the feedback was manipulated to be either a standard or an oddball. Critically, our results showed that feedback stimulus type did not have any effect on the reproduced durations.

Participants across the four oddball experiments performed a temporal reproduction task where they had to press and hold the spacebar to reproduce the duration of the stimulus. Temporal reproduction tasks have been shown to induce non-linear motor responses in duration judgment tasks. For example, Droit-Volet (Droit-Volet, 2010) has shown that the motor noise non-uniformly affected reproduction judgments for 2.5 and 4.5 sec duration stimuli. Further, age is also an important factor that drives the effect of motor noise in duration judgment tasks (Droit-Volet, 2010). I used temporal reproduction across our experiments since it provided us with a straightforward way to probe the online experience of oddballs. Although the durations of stimuli in our tasks ranged from 750 to 1500 msec, note that the range of durations was constant both across and within the experiments. Thus, any non-uniform effects of motor noise should be averaged out when comparing across the experiments. Moreover, the participants in these studies were of the same age group – age ranged between (18-22) years - which should further minimize the inter-individual effects in oddball duration reproductions.

Another key factor that is common across all four of our experiments is the reward that participants earned after every trial. It has been shown that stimulus specific properties of oddballs might invoke arousal among participants during the oddball paradigm (Ulrich 2001). Thus the obtained reward could be differentially driving the effects for oddballs and standards. This could be a factor driving the results we observed for oddballs in Experiments 1 and 1.1. However, I speculate that the effects of reward should average out when comparing across the four experiments. Further, the absence of any reward related effects in Experiments 2 and 2.1 only highlights the impact of stimulus and task specific factors in memory related distortions, but not in perception.

Collectively, the results from our experiments demonstrate that oddball duration distortions are a result of mechanisms responsible for memory encoding, and that they do not happen in our perceptual experience. Indeed, the results from Experiments 2 and 2.1 suggest that we experience both oddballs and standard stimuli alike.

4.7 Summary

In conclusion, these results show that the online perceptual experience of oddballs and standards was not significantly different from one another. This might seem surprising given the intuitive nature of the concept, but at the same time, it is a concept for which it is hard to imagine a specific mechanism that could actually produce it. In many ways, I take the memory hypothesis that we promoted here as the baseline hypothesis , however, the one that has never been tested previously.

5

Wrinkles and Extensions: Memory based Temporal Distortions

5.1 Introduction

Chapter 04 focused on the phenomenon of the subjective expansion of time. Specifically, it focused on whether time seems to expand in our perceptual experience. By systematically dissociating memory effects from perceptual experience in participant reports, I concluded that subjective distortions of time are a result of our memory, and do not happen in our online experience at least with respect to the kinds of manipulations I examined in the previous chapter. Cognitive factors such as attentional allocation, stimulus repetition, and predictive coding could still impact duration judgments, albeit in memory, although I have not ruled out the effects of such factors on our online experience.

The aim of this chapter is to begin to probe the underlying mechanisms responsible for temporal distortions by asking three questions via three manipulations. The experiments are intended to identify three potentially fruitful future paths and open questions for future research. Experiment 1 investigates the extent to which memory builds an internally *consistent* description of an event based on its encoding of duration. Specifically, is remembered speed—distance over duration—slower than actual when duration expands? Experiment 2 manipulates the onset time of oddball features in the duration reproduction task. Its purpose, similar to that of Experiment 1, is to investigate the coherence of distorted temporal memory by asking if memory is sensitive to changes that occur to an object over the course of an experienced duration. Further, this experiment seeks to investigate questions about what kinds of stimulus properties might be accumulated as the input to duration memory. Finally, Experiment 3 asks a rather different question: are mechanisms for remembering duration the same for the presence of objects compared to 'empty' waiting periods?

5.2 Speed drag

In this set of two experiments I investigated if the observed oddball effects generalize to moving stimuli. Specifically, in the first experiment I replicated the oddball expansion effects with moving stimuli. In the second experiment, I investigated whether the remembered speed of oddballs is also distorted in addition to the duration effects. Participants performed a temporal judgment task where they saw stimuli move on the screen for a given duration. Occasionally, there was an oddball stimulus that moved on the screen. They had to judge whether the oddballs were present on the screen for a longer / shorter duration than the standards - Experiment 1.1; or moved faster / slower compared to standards - Experiment 1.2.

5.2.1 Experiment 1.1: Subjective duration expansion is reported in dynamic stimuli

5.2.1.1 Methods

Participants

36 Amazon Mechanical Turk participants took part in this study. I restricted the population of the participants to the United States, who had a hit rate approval of at

least 85%, and had finished at least 100 hits on Amazon Mechanical Turk. Participants were paid $2.00 for the completion of the study that lasted for about 10-12 minutes. All the study procedures were approved, and conducted in compliance with the guidelines provided by the Homewood Institutional Review Board (HIRB).

Materials

The experiment was coded in JavaScript, and html. I used a forced-response yes/no design for the oddball paradigm to investigate the subjective expansion of time. Participants had to report whether the moving oddball they saw lasted longer or shorter than the moving standard disc. The design for this experiment is illustrated in Figure 26. A demonstration of this experiment can be found here (http://www.au.perceptionresearch.org/Time_Subjective_Expansion/Experiment1_1.html)

Stimuli

A standard disc was a black colored disk that was 125 pixels in diameter. I used three different types of oddballs, an oddball with constantly changing color (type 1), a red colored oddball (type 2), and a circular disc with spikes (type 3). Both the oddballs of type 1 and 2 were 125 pixels in diameter. For the oddball of type 3 (spikes), a square of 112 pixel side was overlaid on top of the 125 pixel standard disc. The animation property of the oddballs with constantly changing color had a color change from dark violet to yellow green of the RGB spectrum linearly in a span of 1 second. All the stimuli appeared at random locations, and moved in random directions with a constant speed of 20% screen width in 1.05 sec. Each oddball appeared and moved on the screen after a randomly chosen number of standard discs between 7 and 13 appeared. Each standard disc lasted on the screen for about 1050 msec. The ISI between each disc was randomly chosen between 950 and 1050 msec. The duration of the oddballs was manipulated from the list of [450, 525, 600, 675, 750, 825, 900, 975, 1050] msec as used in (Tse et al 2004). The order of the durations and the type of oddballs were randomized and counterbalanced throughout the experiment. Each participant saw an oddball type for a given duration only once. Overall there were 30 oddballs - with 10 durations for each of the 3 types — that were randomly embedded in a sequence of standard discs.

Procedure:

Participants saw a total of 30 oddballs overall during the experiment that appeared after an average of 10 standard discs (a randomly chosen number between 7 - 13). The experiment took an average of 10-12 minutes to complete, with a maximum allowed duration of 20 minutes. In the beginning of the experiment they were told that they would be tested on their ability to perceive the duration of how long something lasts on the screen. They were told that they would see black disks appear, move and disappear, and that all the black disks would all last for exactly the same amount of time. Occasionally, they would see things other than a black disk appear, move and disappear — these might be spinning or differently colored things. Their task was to judge whether that "oddball" lasted shorter or longer on the screen than the black disks by pressing the [S] /[L] keys respectively on their keyboard.

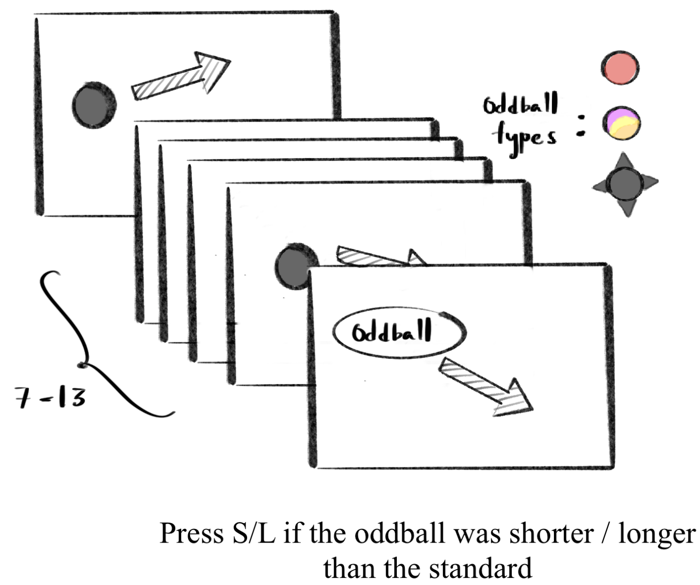

Figure 26 : Design for experiment 1.1 – Speed drag

Participants watched 7-13 moving standard discs before they saw an oddball disc which could be of three types as shown in the figure. Once they saw the oddball, they had to report if the oddball was shorter / longer than the standard by pressing S/L on their keyboard.

5.2.1.2 Results:

Participant responses were coded in terms of 0s and 1s. Each response was considered 1 when the participant's response matched with the objective ground truth, and 0 otherwise. I then computed the Weibull psychometric curve fit to estimate the point of subjective equality using the coded responses for each of the durations averaged across all the oddball types. The estimated PSE of the fit is 851 msec. This suggests that participants perceived an oddball of around 850 msec to last as long as a 1050 msec standard disc. See Figure 27.

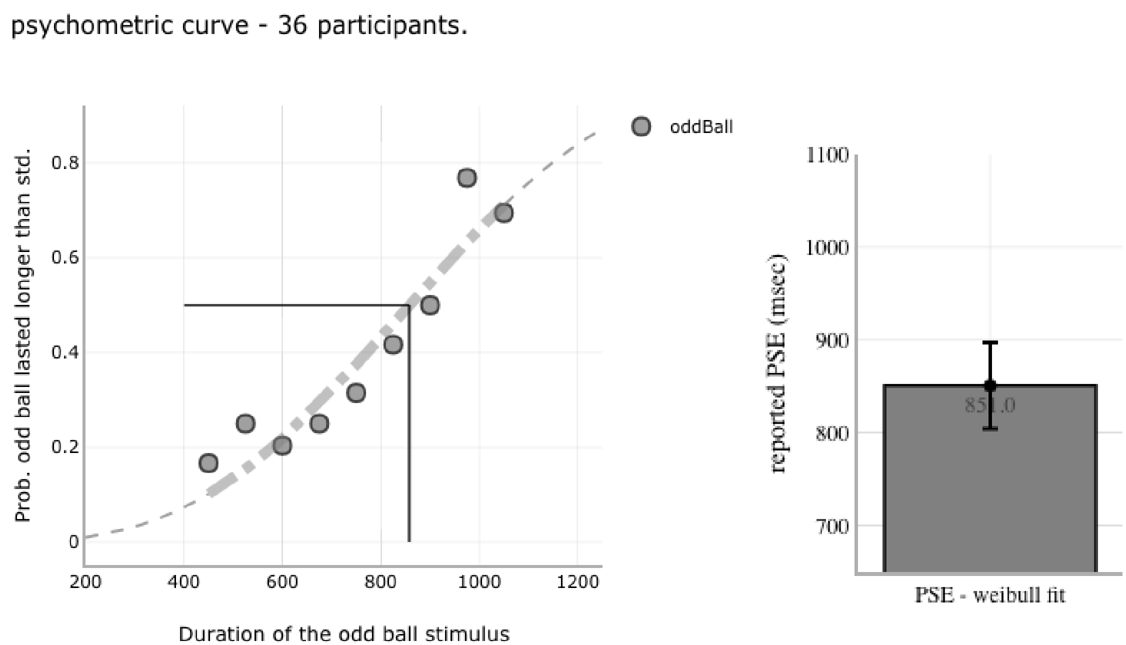

Figure 27 : Estimated PSE from experiment 1.1 – Speed Drag

a) Illustrating the psychometric curve fit for the oddball duration in relation to the standards. b) Point of Subjective Equality observed.

5.2.1.3 Discussion:

In this experiment, I had participants on MTurk perform an oddball paradigm in which they had to compare the duration of an oddball to standard discs by pressing S/L to indicate if the oddball was shorter/longer than the standards. Overall these results replicate the classic laboratory findings that oddballs are perceived to last longer than standards. This replication is interesting because I found a robust effect of oddballs in spite of the discs starting at random positions and moving with random headings. Further, the stimuli including standard discs were moving for the entire duration of their presence. I conducted another experiment based on this design to measure whether participant reports of the speed of the oddballs is distorted similar to the duration reports.

5.2.2 Experiment 1.2: Speed drag observed for oddball stimuli

In this experiment, I investigated the extent to which memory builds an internally c*onsistent* description of an event based on its encoding of duration. Specifically, if the remembered speed of oddballs is perceived as slower than they actually were. Speed is defined as the distance traveled by an object over a period of time. If our memories of time are distorted by the uniqueness of the event, then it might be possible that time derived quantities such as velocity are also affected by such distortions. I predicted that oddballs that are remembered to be lasting longer than their objective duration will also be remembered as moving more slowly when compared to the standards. To test this hypothesis, I used the same oddball paradigm in Experiment 1.1, but with a slight modification (see materials). Instead of asking participants to compare the duration of the oddballs, here I asked them to compare the speed with which the oddballs moved as opposed to standards.

5.2.2.1 Methods

Participants:

36 Amazon Mechanical Turk participants took part in this study. Just like in Experiment 1.1, I restricted the population of the participants to the United States, who had a hit rate approval of at least 85%, and had finished at least 100 hits on Amazon Mechanical Turk. Participants were paid $2.00 for the completion of the study that lasted for about 10-12 minutes. All the study procedures were approved, and conducted

in compliance with the guidelines provided by the Homewood Institutional Review Board (HIRB).

Materials:

The experimental design for Experiment 1.2 was very similar to Experiment 1.1 except for a slight modification. The duration of the oddballs was also fixed at 1050 msec unlike Experiment 1.1. Thus, both the oddballs and the standard discs objectively moved at the same speed. Ideally, participant responses should not be different from chance level (50%) because there is no correct answer. However, I hypothesized that if the subjective time expansion of oddballs makes them remembered as moving slower, then we should expect participant responses to be significantly different than chance. The order of the oddball types were randomized and counterbalanced throughout the experiment. Each participant saw an oddball type for a given duration three times. Overall there were 30 oddballs - with 10 repetitions for each of the 3 types - that were randomly embedded in a sequence of standard discs.

Procedure:

Participants saw a total of 30 oddballs overall during the experiment that appeared after an average of 10 standard discs (a randomly chosen number between 7 and 13). The experiment took an average of 10-12 minutes to complete, with a maximum allowed duration of 20 minutes. At the beginning of the experiment, participants were told that they would see black disks appear, move and disappear, and that all the black disks would all last for exactly the same amount of time. Occasionally, they would see things other than a black disk appear, move and disappear — these might be spinning or differently colored things. Their task was to judge whether that "oddball" moved slower or faster on the screen than the black disks by pressing the [S] / [L] keys respectively on their keyboard.

5.2.2.2 Results:

Participant responses were coded in terms of 0s and 1s. Each response was considered 1 when the participant said the oddball moved faster, and 0 otherwise. I then computed the probability with which each participant said the oddball moved faster for each of the oddball types. Thus each participant ($n = 36$) had an average probability for each of the three oddball types. I did a one sample t-test to check if the probabilities were significantly different from chance level 50%. Overall, participants reported that the oddballs moved slower compared to the standards approximately 55% of the time, $t(107) = -2.38$, $p = 0.01$ (see Figure 28). A one sample t-test analysis for each of the oddball type revealed that participants perceived oddballs of the type 1 and 2 (changing color $t(35) = -3.06$, $p = 0.004$, and red color $t(35) = -.203$, $p = 0.049$) to be moving slower than the standards, but not for the spike category. However, there was no significant difference in the probability reports of oddball type 3 (spiked oddball) compared to the chance level. This is possibly because of the shape similarity of the oddball type 3 with the standard disc. The spike oddball was a regular standard disc with an overlaid square on top of the circle.

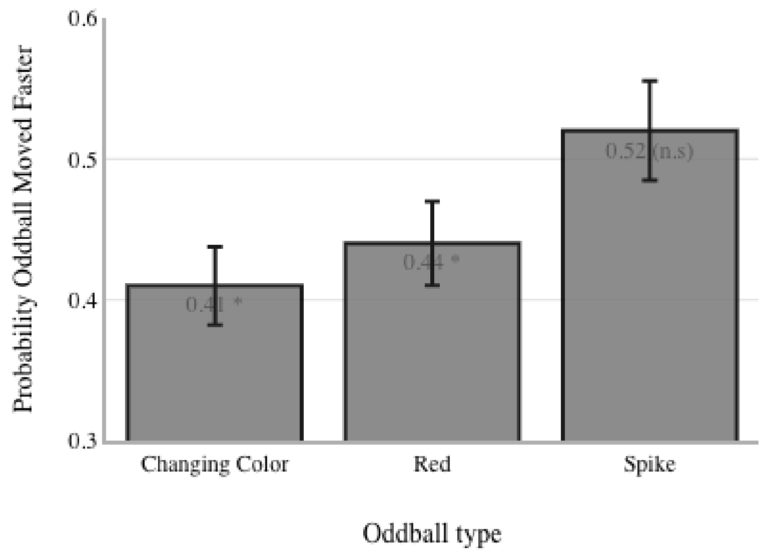

Figure 28 : Results from the speed drag experiment 1.2 – Speed Drag

Probability with which participants said that the oddballs moved faster than the standards even when they all moved at the same speed for the same time grouped by the oddball type.

5.2.2.3 Discussion:

Experiment 1.1 replicated the classic laboratory finding of subjective expansion of time online. The results from Chapter 04 suggest that subjective expansion of time is a memory phenomenon, and that the online experience of oddballs and standards are not different from one another. In this experiment, I investigated whether moving oddballs are remembered as moving slower compared to the standards. Accordingly, we asked participants to judge the speed with which the oddballs moved in comparison to the standard discs. Both the oddballs and the standard discs objectively moved at the same speed. If speed is not affected by the memory distortions like duration judgments are, then we should expect that participants should be at chance level saying if the oddballs moved faster / slower than the standard discs. However, I found that participants significantly reported the oddballs as moving slower than the standard discs. These results are interesting because they suggest a consistency in distortions of remembered oddball experiences. In particular, speed is defined as the distance traveled over time. The speed drag (aka oddballs moving slower than standards) and duration expansion (aka oddballs lasting longer than standards) reports for the oddballs point towards conceptually consistent memory distortions. Together, these experiments suggest that memory is sensitive to the motion components of the stimuli that were experienced. Experiment 2 explored the distortions in memory as a function of another type of change that might happen in stimuli over the time period. Specifically, I explored how changes in the oddness property of oddballs affects distortions in memory.

5.3 Experiment 2: Manipulating the oddness onset of the oddballs

One commonly replicated finding across all the oddball paradigms is that oddballs are reported as lasting longer the standard discs. Typically what makes oddballs odd compared to other stimuli in the task is that oddballs have one or two non-temporal properties that are different from the regular stimuli. For example, colored / looming stimuli in a sequence of black discs. In addition, all the oddballs have been odd throughout their presentation right from the appearing on the screen. These oddballs thus have an oddness onset of 0, i.e., they appeared as oddballs at 0 msec into their presentation on the screen. In this experiment, I explored the consequences of oddness onsets on temporal duration judgments. Specifically, I manipulated the oddness onset of an oddball to see how it affected participant responses. A demonstration of this experiment can be found at http://www.au.perceptionresearch.org/Exp3.1gameOnTP/Tachypsychia-experiment3.html?workerId=3769

5.3.1 Methods

Participants:

63 Johns Hopkins undergraduates took part in this study on an online platform (www.sona-systems.com) for course related credit. All the participants had normal / corrected-to-normal vision. All the study procedures were approved, and conducted in compliance with the guidelines provided by the Homewood Institutional Review Board (HIRB).

Materials:

The experiment was coded using html and JavaScript. In a given trial, there were 4 stimuli each presented in the center of the screen with a white background. The first three discs were always standard stimuli with the dimensions of 250 pixels of width and height. The fourth stimulus was an oddball (a looming disc) which expanded with a rate of 0.125 pixels for every refresh frame. Further, the fourth stimulus sometimes did not start as a looming disc. It was a standard disc for some time (aka onset time) before it started looming. We manipulated the oddness onset to be either at 0% (0), 40% (0.4), 60% (0.6) or 100% (1.0) of the given trial duration. An oddness onset of 0% (0.0) would imply that the fourth stimulus started out as an oddball. Likewise, an oddness onset of 100% (1.0) would imply that the fourth stimulus was an oddball after the entire duration has elapsed. In other words, the fourth stimulus was never an oddball, i.e., it was always a standard disc for the oddness onset of 1.0. I used ten different durations ranging from 750 to 1525 msec - [750, 825, 900, 975, 1050, 1125, 1250, 1375, 1450, 1525] msec. There were a total of 80 trials, 20 for each oddness onset condition. The 20 trials for each oddness condition contained 2 repetitions of the given trial for the 10 mentioned durations. All the participants had the same design as mentioned. The order of the durations and stimulus conditions in each trial was randomized.

Procedure:

Participants performed a total of 80 trials overall during the experiment. The experiment took an average of 15-20 minutes to complete. At the beginning of the experiment, participants were told that they would be examined on their ability to perceive durations, i.e., how long something lasts on a screen. They were told that there would be 4 black discs appearing sequentially on a given trial. The first three of them were always the same, and the fourth disc could be either same or different. Their task was to reproduce the duration of the fourth disc by pressing and holding the spacebar for as long as they thought the stimulus was present on the screen.

In addition, participants were told that they would be playing a game version of the task where they would be awarded for reproducing the durations of the stimuli they saw. They were instructed to be as accurate as possible in reproducing the duration. This was enforced by awarding them points in each trial. Each trial was for 10 points, and the experiment was for a total of 800 points. The amount they earned in each trial dropped exponentially as a function of the difference in reproduced and actual durations. They were told that their course credit would be doubled if they scored 450/800 points, although everyone received double the course credit for participation. No points were awarded in a trial if they went over the duration.

5.3.2 Results

There were a total of 63 participants in this experiment. Since this was an online replication, I had to do some data cleaning. Depending on how long the participants took to finish the experiment, I filtered out participants who took longer than 50 minutes to perform the experiment. Additionally, since the maximum duration of the stimulus was 1500 msec, I also filtered out subjects whose reproduced durations were greater than 2000 msec. This meant that there were a total of 54 participants in our experiments. For each participant, I collected the reproduced duration of each stimulus type in a given trial. The data were subject to an ANOVA test with reproduced duration as the dependent variable, and objective duration, and oddness onset as predictor variables. I found a significant main effect of duration ($F(1, 4315) = 1746.77$, $p < 0.0001$), and the oddness onset ($F(3, 4315) = 54.74$, $p < 0.0001$). The interactions between duration and oddness onset conditions were not significant. Further, planned contrasts revealed that participant reports decreased significantly with increasing oddness compared to the baseline condition (oddness onset 0.0) $t(4314) = -7.07$, $p < 0.001$ (for oddness onset 0.4); $t(4314) = -9.23$, $p < 0.001$ (oddness onset 0.6); and $t(4314) = -12.31$, $p < 0.0001$ (oddness onset 1.0) (one-tailed) [See Table 5] for more details]. Together these results suggest that the oddness onset had a significant effect on the duration reproduction task as can be seen from Figure 29 and Figure 30.

	Df	$SumSq$	$MeanSq$	$Fvalue$	$Pr(> F)$
$X1.duration$	1	80139979.78	80139979.78	1746.77	0.0000
$oddOnset$	3	7533736.03	2511245.34	54.74	0.0000
$Residuals$	4315	197967207.30	45878.84		

	$Estimate$	$Std.\ Error$	$tvalue$	$Pr(> \|t\|)$
$(Intercept)$	330.5816	15.7284	21.02	0.0000
$X1.duration$	0.5330	0.0128	41.79	0.0000
$oddOnset0.4$	−65.1272	9.2174	−7.07	0.0000
$oddOnset0.6$	−85.0785	9.2174	−9.23	0.0000
$oddOnset1$	−113.4864	9.2174	−12.31	0.0000

Table 5 : ANOVA and Linear Model results for experiment 2

Output of the linear regression model with reproduced duration as the dependent variable, and duration and oddness onset (categorical) as predictor variables, and the F-statistic computed using ANOVA.

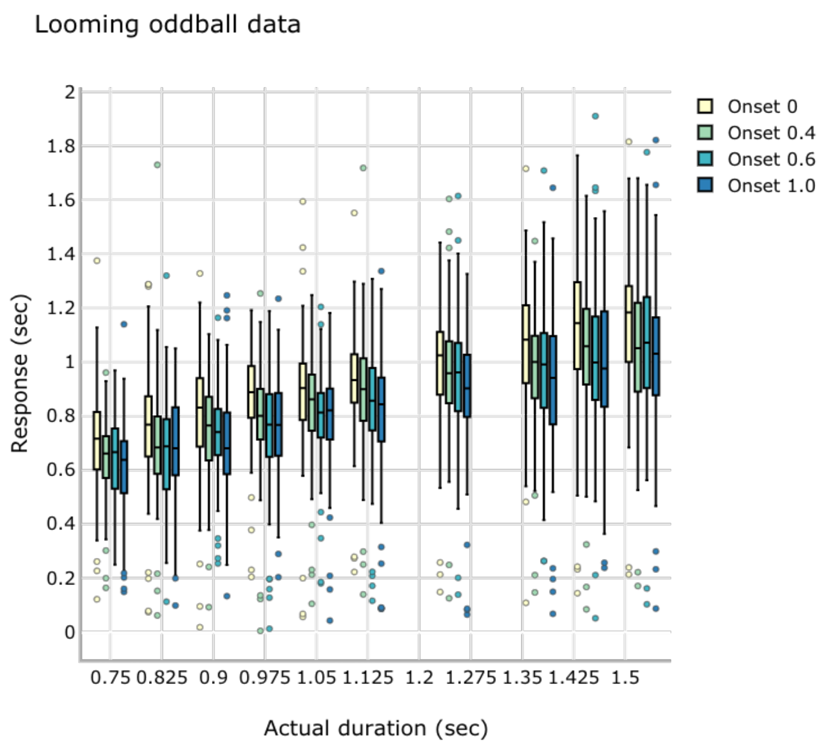

Figure 29 : Raw data for experiment 2 – Oddness onset

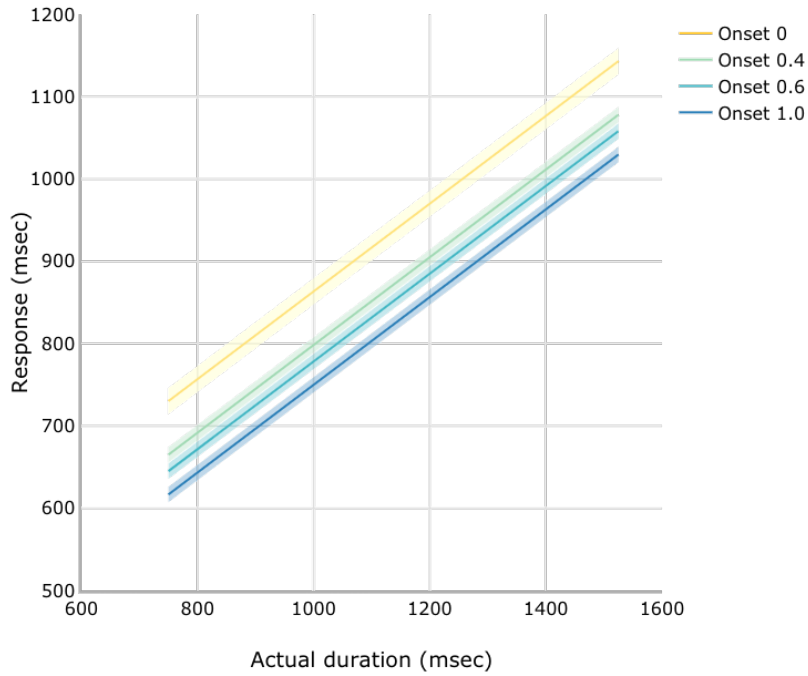

Figure 30 : Results for model fit for experiment 2 – Oddness onset

Results of the fitted model for each of the oddness onset conditions. Y axis is the reproduced judgment (in msec), and X axis is the actual duration of the stimulus (in msec).

5.3.3 Discussion

In this experiment, I investigated whether oddness onset of the stimulus plays an important role in predicting the subjective expansion of duration judgments. Participants reproduced the durations of the oddball discs whose oddness onsets were manipulated to either start at the beginning / middle / end of the duration of the stimuli. The comparison between oddness onset at 0 (complete oddballs) and oddness onsets 1 (regular standard discs) revealed an expansion effect for the oddballs compared to the standard discs replicating the subjective expansion effects observed in the oddball paradigms (Eagleman & Pariyadath, 2009; Pariyadath & Eagleman, 2007, 2008, 2012; Tse et al., 2004). Moreover, participant reports for oddballs decreased significantly with late oddness onsets. Why are participant reports decreasing with oddness onsets? One explanation favors the change accumulation hypothesis (Block & Reed 1978; Poynter 1989; Brown 1995). According to this account, subjective duration distortions are driven by the amount of information accumulated over time during the given duration. Note that all the oddballs in this experiment were looming discs – discs that change dynamically throughout their duration. In the case of looming oddballs with late oddness onsets, the amount of looming displayed on the screen would be smaller compared to the oddballs with early onsets. Thus, if looming amount is a type of information that is encoded into the remembered duration of these oddballs, the information accumulation would then predict that the oddballs with later onsets are perceived as lasting shorter than early onset oddballs. This prediction is consistent with the observed results.

Alternatively, it is possible that participants might be just reporting the duration for which the oddballs were odd. For example, consider the oddness onset 0.6 example. In this scenario, the stimulus remained as a standard disc for 60% of its duration before looming for the remaining 40% of its duration. If participants only reported the looming duration (i.e., the 40%) instead of the entire duration, that would also predict that the oddballs with later oddness onsets would be reported as shorter compared to early oddness onsets.

I believe that one of my earlier versions of this oddness onset experiment can be useful in drawing the distinction between the above mentioned two explanations. This experiment was a conceptual replication of Experiment 2. Here, participants performed the oddness onset task with both color & looming oddballs. I hypothesized that if participants were reporting just the duration for which the stimulus was an oddball, then a similar trend in oddness onset reports should be observed for the colored oddballs. On the other hand if the reports are driven by the information accumulation account, then we might expect a different trend in the reports for colored oddballs – since the amount of information accumulated over time in colored and looming oddballs is not the same.

5.4 Experiment 2.1: Conceptual replication - Manipulating the oddness onset of the oddballs

In this experiment, participants performed a temporal reproduction task on both colored and looming oddballs with varying oddness onsets. A demonstration of this task can be found here : http://www.au.perceptionresearch.org/Exp3gameOnTP/Tachypsychia-experiment3.html?workerId=3769

5.4.1 Methods

Participants:

64 Johns Hopkins undergraduates took part in this study on an online platform (www.sona-systems.com) for course related credit. All the participants had normal / corrected-to-normal vision. All the study procedures were approved, and conducted in compliance with the guidelines provided by the Homewood Institutional Review Board (HIRB).

Materials:

The materials for this experiment were similar to that of the previous experiment. However, the fourth oddball stimulus was either a color oddball or a looming oddball or a standard disc. Additionally, I manipulated the oddness onset for oddballs to be either at 0% (0), 40% (0.4), 60% (0.6) of the given trial duration. I used ten different durations ranging from 750 to 1525 msec - [750, 825, 900, 975, 1050, 1125, 1250, 1375, 1450, 1525] msec. There were a total of 90 trials, 30 for each of the stimulus conditions. Within each stimulus condition, there were 3 trials for each of the 10 durations. Further, within each of the three trials for a given duration in each of the oddballs, there was one trial each for the three different oddness onsets. All the participants had the same design as mentioned. The order of the durations, stimulus conditions and oddness onsets in each trial was randomized. The experiment on average took about 20-25 minutes to complete.

5.4.2 Results:

There were a total of 64 participants in this experiment. Since this was an online replication, I had to do some data cleaning. Depending on how long the participants took to finish the experiment, I filtered out participants who took longer than 50 minutes to perform the experiment. Additionally, since the maximum duration of the stimulus was 1500 msec, I also filtered out subjects whose reproduced durations were greater than 2000 msec. This meant that there were a total of 50 participants in our experiments. For each participant, I collected the reproduced duration of each stimulus type in a given trial. Due to the complex structure of the experimental manipulation, I separated the data into colored and looming oddball data for the 50 participants with 10 durations and 3 oddness onset conditions. Each of the color and looming data were subject to an ANOVA test with reproduced duration as the dependent variable, and objective duration, and oddness onset as predictor variables.

Analysis for looming oddballs with oddness onsets

I found a significant main effect of duration ($F(1, 1496) = 582.63$, $p < 0.0001$), and the oddness onset ($F(2, 1496) = 9.78$, $p < 0.0001$). The interactions between duration and oddness onset conditions were not significant. Further, planned contrasts revealed that participant reports decreased significantly with increasing oddness compared to the baseline condition (oddness onset 0.0) $t(1495) = -2.09$, $p < 0.05$ (for oddness onset 0.4); $t(1495) = -4.42$, $p < 0.001$ (oddness onset 0.6) (one-tailed) [See Table 6 for more details]. Together these results suggest that the oddness onset had a significant effect on the duration reproduction task for looming oddballs as can be seen from figure 5.

	Df	*SumSq*	*MeanSq*	*Fvalue*	*Pr*($ > $*F*)
*X*1.*duration*	1	25778396.30	25778396.30	582.63	0.0000
oddOnset	2	865051.24	432525.62	9.78	0.0001
Residuals	1496	66190320.98	44244.87		

	Estimate	*Std. Error*	*tvalue*	*Pr*($ > $$|$*t*$|$)
(*Intercept*)	363.3733	25.6435	14.17	0.0000
*X*1.*duration*	0.5130	0.0213	24.14	0.0000
*oddOnset*0.4	−27.7789	13.3034	−2.09	0.0370
*oddOnset*0.6	−58.7938	13.3034	−4.42	0.0000

Table 6 : ANOVA and Linear Model results for Looming oddballs experiment 2.1 – Conceptual replication of oddness onset.

Output of the linear regression model with reproduced duration as the dependent variable, and duration and oddness onset (categorical) as predictor variables, and the F-statistic computed using ANOVA.

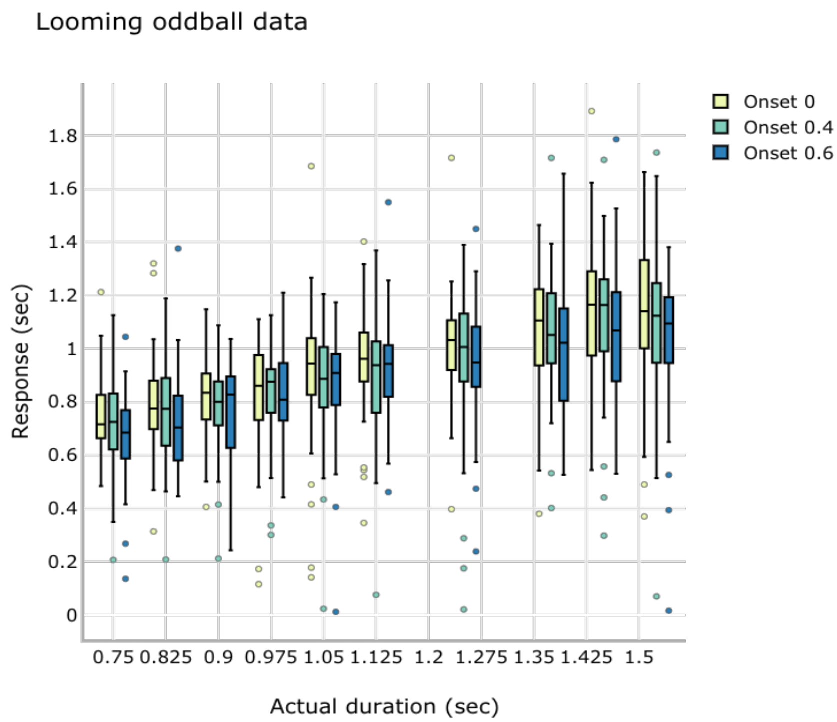

Figure 31 : Raw data for Looming oddballs in experiment 2.1 – Conceptual replication of oddness onset.

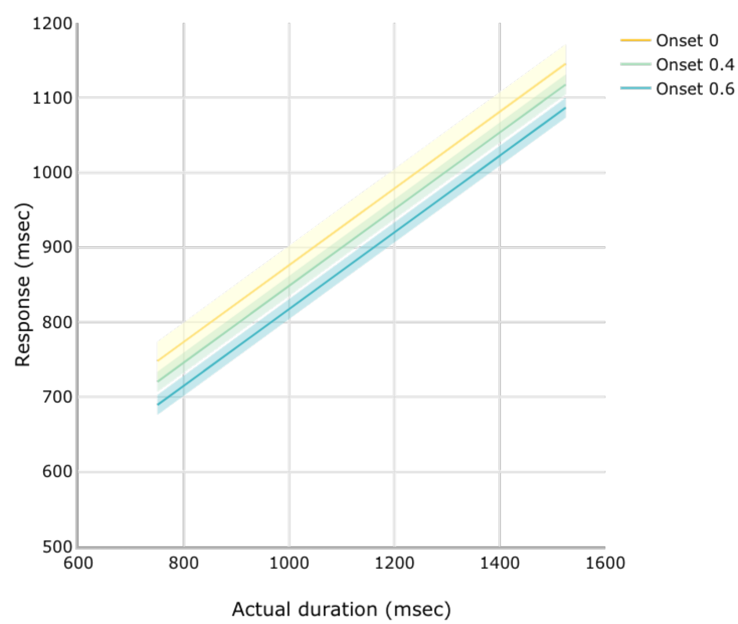

Figure 32 : Results for Looming oddballs in experiment 2.1 – Conceptual replication of oddness onset

Y axis is the reproduced judgment (in msec), and X axis is the actual duration of the stimulus (in msec).

Analysis for color oddballs with oddness onsets

I found a significant main effect of duration (F(1, 1496) = 449.25.63, p < 0.0001). However, there was no significant main effect of the oddness onset (F(2, 1496) = 0.96, p = 0.38). The interactions between duration and oddness onset conditions were not significant. Further, planned contrasts revealed no significant differences between oddness onset conditions and the baseline: t(1495) = -0.72, p = 0.46 (for oddness onset 0.4); t(1495) = -1.39, p = 0.16 (oddness onset 0.6) (one-tailed) [See Table 3 for more details]. Together these results suggest that the oddness onset had no significant effect on the duration reproduction task for color oddballs as can be seen from figure 5.

	Df	*SumSq*	*MeanSq*	*Fvalue*	*Pr*($ > $*F*)
*X*1.*duration*	1	21819513.69	21819513.69	449.25	0.0000
oddOnset	2	93608.47	46804.23	0.96	0.3817
Residuals	1496	72658805.77	48568.72		

	Estimate	*Std. Error*	*tvalue*	*Pr*($ > $$|$*t*$|$)
(*Intercept*)	336.4461	26.8673	12.52	0.0000
*X*1.*duration*	0.4720	0.0223	21.20	0.0000
*oddOnset*0.4	−10.0774	13.9383	−0.72	0.4698
*oddOnset*0.6	−19.3446	13.9383	−1.39	0.1654

Table 7 : ANOVA and Linear Model results for Colored oddballs in experiment 2.1 – Conceptual replication of oddness onset

Output of the linear regression model with reproduced duration as the dependent variable, and duration and oddness onset (categorical) as predictor variables, and the F-statistic computed using ANOVA.

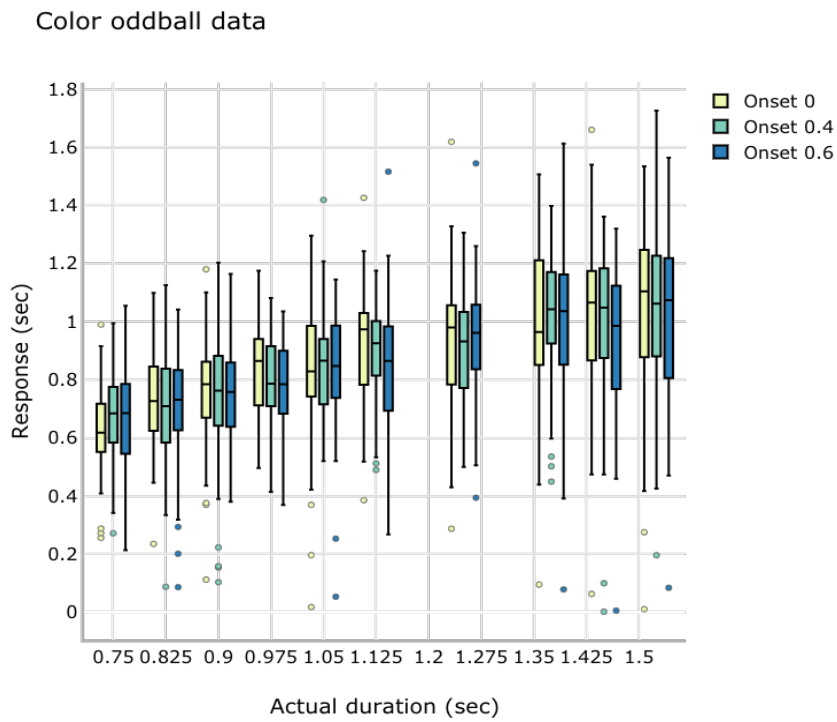

Figure 33 : Raw data for Colored Oddballs in experiment 2.1 – Conceptual replication of oddness onset.

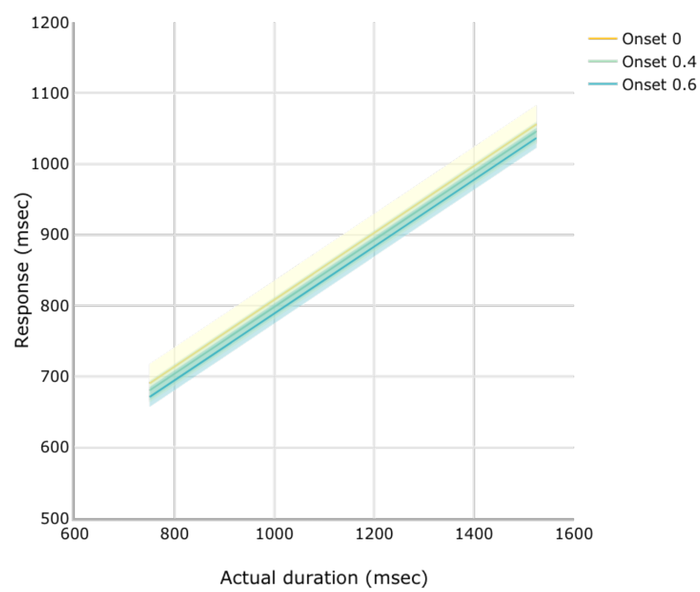

Figure 34 : Results for Colored Oddballs in experiment 2.1 – Conceptual replication of oddness onset.

Y axis is the reproduced judgment (in msec), and X axis is the actual duration of the stimulus (in msec).

5.4.3 Discussion

This experiment is a conceptual replication of Experiment 2 - where I found a significant effect of oddness onset on duration reproductions. In particular, participants reported the durations of oddballs with late oddness onsets as shorter compared to the early oddness onsets. I identified two explanations for these observed results: 1) The amount of information accumulated for oddballs decreased as a function of oddness onset. According to the information accumulation account, oddballs with late oddness onsets accumulated less information compared to the ones with early odd onsets. Thus resulting in shorter duration reproductions for oddballs with late oddness onsets. 2) Participants might be reporting only the duration for which the oddballs were odd. In other words, they might just be reporting the durations since oddness onset. I hypothesized that if this second explanation is driving these results, then the same trend should be observed for the oddballs of a different type. Accordingly, the results from this replication experiment identify two key points: 1) The oddness onset had a significant effect on the reproduced durations for looming oddballs - an effect which I replicated from an earlier experiment. 2) There was no effect of oddness onset on the reproduced durations of the colored oddballs even though the oddness onsets were the same for both colored and looming oddballs. This result rules out the possibility that participants are reporting just the duration of oddballs after oddness onset. However, this raises an interesting question about the lack of oddness onset effects on colored oddballs. Why did the oddness onset not have an effect on color oddballs?

One possible explanation again concerns the information accumulation account. This account predicts that the distortions in the duration judgments are predicted by the amount of information accumulated from the stimulus during the duration. In the case of color oddballs, the change in color happens at the oddness onset and it remains the same for the remainder of the stimulus duration. Therefore, the total amount of information accumulated is the same for various oddness onsets in the case of the colored oddballs. This would explain the lack of oddness effects on the colored oddballs. Furthermore, the information account hints at the possibility that oddballs are remembered longer because of the amount of information that is accumulated during their presence on the screen. Together these results highlight the effects of oddness onset and information accumulation on the reproduced durations of the oddballs. They also invite potential research questions on the information accumulation theory for future work to explore. In the next experiment, I investigated the information accumulation hypothesis further. Specifically, I explored how participants' estimates for duration change when they are asked to reproduce the duration of experienced emptiness on the screen as opposed to experiencing a stimulus.

5.5 Experiment 3: Duration judgments in the presence and absence of a stimulus

In this experiment, I investigated how duration judgments are affected by the presence and absence of the stimulus. Participants performed a simple temporal reproduction task where they saw a sequence of discs. Participants were then asked to either report the duration of the blank duration between the two stimuli, or the duration of the stimuli itself depending on the experiment condition. A demonstration of the experiment can be found here http://www.au.perceptionresearch.org/Exp4.1gameOnTP/Tachypsychia-experiment4_1.html and here http://www.au.perceptionresearch.org/Exp4.2gameOnTP/Tachypsychia-experiment4_2.html

5.5.1 Methods

Participants:

109 Johns Hopkins undergraduates took part in this study on an online platform (www.sona-systems.com) for course related credit. All the participants had normal / corrected-to-normal vision. All the study procedures were approved, and conducted in compliance with the guidelines provided by the Homewood Institutional Review Board (HIRB).

Materials:

This experiment had two conditions that were tested independently (I.e. each with a different group of participants). The two conditions were: stimulus absent condition, and stimulus present condition. A given trial in the stimulus absent condition consisted of four discs each lasting for 750 msec with a variable ISI between the two discs. Each black disc had the dimensions of 250 pixels in both width and height. There were three blank spaces embedded within the four black discs. Participants were instructed to judge the duration of the blank space between the two discs.

A given trial in the stimulus present condition consisted of three black discs each subtending 250 pixels in width and height on the screen. The ISI (interstimulus interval) between the two discs was 750msec. The duration of the discs was variable.

Participants in this condition were instructed to report the duration of the stimuli (black discs).

In both the stimulus present and absent conditions I used ten different durations ranging from 750 to 1525 msec - [750, 825, 900, 975, 1050, 1125, 1250, 1375, 1450, 1525] msec. The duration of the ISI (blank space) was chosen from these 10 durations in the stimulus absent condition, and the duration of the black disc was chosen from these 10 durations in the stimulus present condition. There were a total of 80 trials, 40 for each of the stimulus present and absent conditions. Within each condition, there were four trials for each of the 10 durations. The order of the durations, stimulus conditions and oddness onsets in each trial was randomized. The data for the two conditions were collected separately with 55 participants in the stimulus present condition and 54 in the stimulus absent condition. Each condition on an average took about 10-15 minutes to complete. The procedure for this experiment was similar to that of the previous experiments. Participants earned a reward of up to 10 points on every trial. They were not rewarded for exceeding the actual duration in their reproductions.

5.5.2 Results

There were a total of 109 participants in this experiment. Since this was an online experiment, I had to do some data cleaning. Depending on how long the participants took to finish the experiment, I filtered out participants who took longer than 50 minutes to perform the experiment. Additionally, since the maximum duration of the stimulus was 1500 msec, I also filtered out subjects whose reproduced durations were greater than 2000 msec. This meant that there were a combined total of 90 participants in our experiment in both the conditions. For each participant, I collected the reproduced duration of each stimulus type in a given trial. The data were subject to an ANOVA test with reproduced duration as the dependent variable, and objective duration, and stimulus condition (present / absent) as predictor variables. I found a significant main effect of duration ($F(1, 3646) = 207.86$, $p < 0.0001$), and the stimulus condition($F(1, 3646) = 62.64$, $p < 0.0001$). The interactions between duration and stimulus conditions were not significant. Further, planned contrasts revealed that participant reports differed significantly for the stimulus present compared to the absent condition $t(3645) = -7.95$, $p < 0.001$ (one-tailed) [See Table 4 for more details]. Together these results suggest that presence of a stimulus had a significant effect on the duration reproduction task as can be seen from figure 5.

	Df	*SumSq*	*MeanSq*	*Fvalue*	*Pr*($ > $*F*)
Stimulus_condition	1	5.47	5.47	62.64	0.0000
duration	1	18.16	18.16	207.86	0.0000
Residuals	3646	318.57	0.09		

	Estimate	*Std. Error*	*tvalue*	*Pr*($ > $$|$*t*$|$)
(*Intercept*)	0.5446	0.0227	24.02	0.0000
Stimulus_condition[1]	−0.0782	0.0098	−7.95	0.0000
duration	0.2757	0.0191	14.42	0.0000

Table 8: ANOVA and Linear Model results for blank duration judgments experiment

Output of the linear regression model with reproduced duration as the dependent variable, and duration and stimulus condition (categorical) as predictor variables, and the F-statistic computed using ANOVA.

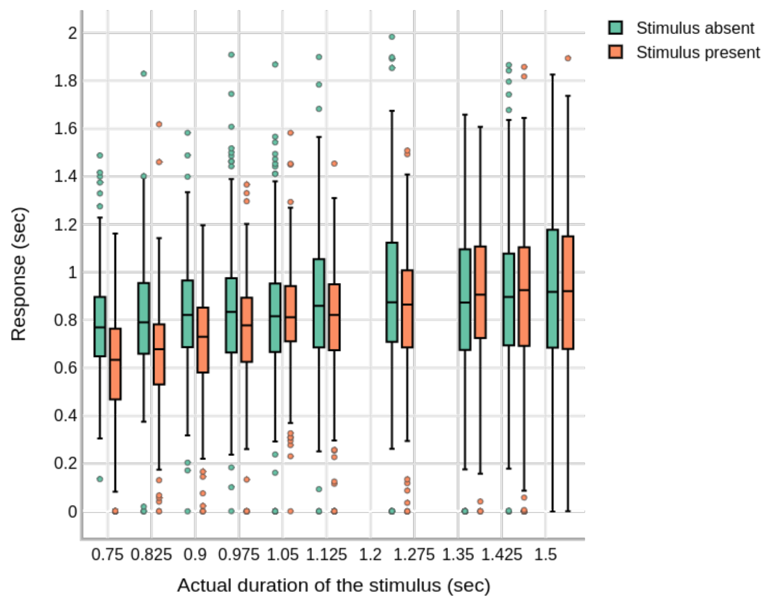

Figure 35 : Raw data for blank duration judgment experiment

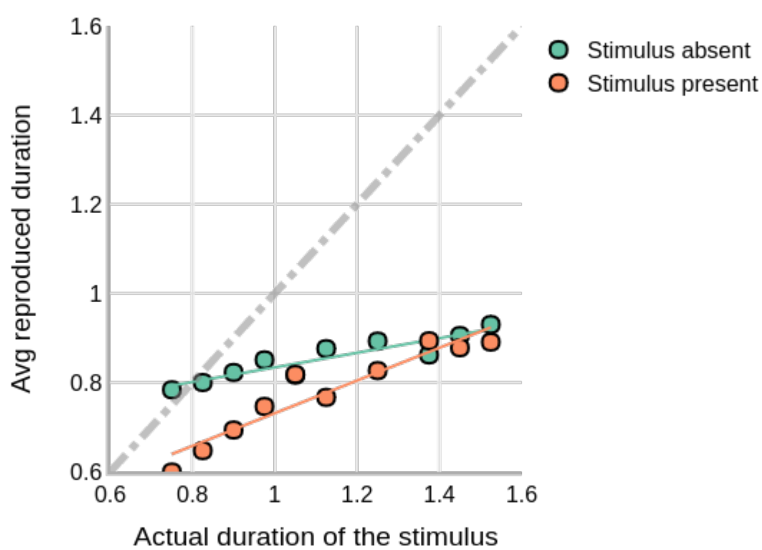

Figure 36 : Results showing the model fits for the blank duration experiment

Y axis is the reproduced judgment (in msec), and X axis is the actual duration of the stimulus (in msec).

5.5.3 Discussion

In this experiment, I investigated how temporal reproductions of duration would vary as a function of the amount of information available. Specifically, I asked whether participant reports of duration judgments would be significantly different when they are asked to judge the duration of the blank screen vs. when they are asked to judge the duration of a scene when a stimulus is present. These results demonstrate a significant difference in reports for both the stimulus present and absent conditions. Specifically, participants reported the durations for the stimulus absent conditions were significantly longer compared to the stimulus present conditions. These results pose a challenge to the information accumulation account. According to this account, the distortions of duration are predicted by the amount of information accumulated during that particular duration. Accordingly, the results from the oddness onset studies and the replications of subjective expansion experiments have shown greater expansion effects for looming oddballs compared to the color oddballs – since looming oddballs are dynamic and accumulate more information over time compared to the color oddballs. An implication for this theory would be that duration judgments for stimulus absent condition in this experiment would be shorter compared to the stimulus present condition. This is because the amount of information accumulated is higher for the stimulus present condition. However, I observed the opposite, i.e., stimulus absent conditions were reported to last longer than stimulus present conditions for the same objective duration.

One possible explanation is that there presence of an object influences encoding of duration judgments. However, past research by New & Scholl (New & Scholl, 2009) has argued that duration judgments are not influenced by manipulations of objecthood that drive object based attention. The reasons for why empty duration judgments are reported as lasting longer than judgments involving presence of a stimulus are unclear. At the very least these results suggest that there are different mechanisms underlying duration judgments for when a stimulus is present vs. absent, and identify potential open questions for future research.

5.6 General discussion

In this chapter, I further investigated the underlying mechanisms responsible for temporal distortions by asking three questions via three manipulations. The experiments discussed here identify three potentially fruitful future paths and open questions.

Experiment 1 investigated the extent to which memory builds an internally c*onsistent* description of an event based on its encoding of duration. Specifically, these results demonstrate that in addition to reporting the oddballs as lasting longer, participants also judged them to move slower compared to the standards even though they all objectively moved at the same speed.

Experiment 2 manipulated the onset time of oddball features in the duration reproduction task. Specifically, I investigated whether duration reports are sensitive to the oddness onset of an oddball. These results show oddness onset was a significant factor in predicting the reproduced durations of the oddballs. Participants reported the duration of looming oddballs with late oddness onset as lasting shorter compared to the early oddness onset oddballs. One potential explanation for these results is that participants might be reporting the durations for which the oddballs were odd instead of the entire duration. For example, it is possible that participants are reporting just the 400 msec duration of the oddball that is 1 second long with oddness onset at 0.6 (i.e. 60%

into the duration). If this were true, similar effects should be present in the oddness onset manipulations of the colored oddballs. However, I did not find any such effects with the colored oddballs.

The absence of oddness onset effects on the colored oddballs clarifies two important questions: 1) Participants were not reporting the duration for which the oddballs were odd. Note that both the looming and colored oddballs had the same objective duration for which they were both odd. For example, in a given duration of 1 sec, both the colored and looming oddballs with an oddness onset of 0.6 were odd for an equal duration of 400 msec. Therefore, if participants were just reporting the duration for which the stimuli were odd, then we should have observed similar oddness onset effects on colored oddballs. This suggests that participants were not just reporting the duration for which the stimulus was odd. Rather, they were reporting the entire duration for which the stimulus was displayed on the screen. 2) Lack of oddness onset on the colored oddballs can be explained by the information accumulation account which posits that the distortions in experienced duration can be explained by the total amount of information accumulated during that duration. Color oddballs whilst different from standards, do not change much during the presentation compared to the looming oddballs. Accordingly, the total amount of information accumulated for color oddballs does not differ with the oddness onset. This would explain the absence of observed effects of oddness onset on the colored oddballs. More importantly, these experiments collectively highlight the significance of information accrual on the reported distortions of duration.

Finally, Experiment 3 asked a related but different question: are mechanisms for remembering duration the same for the presence of objects compared to ‘empty’ waiting periods? These results demonstrate that participant reports for duration judgments with and without stimulus presence were significantly different. Specifically, for a given objective duration, the reports for the stimulus absent condition were higher than the stimulus present condition. Note that this is in contrast with the information accumulation account – which predicts that stimulus present condition to be judged as longer compared to the stimulus absent condition. At the very least, these results suggest that the mechanisms underlying duration judgment for empty waiting periods are different compared to the presence of objects.

Collectively the three themes described in this chapter set the stage for future experiments to investigate the underlying mechanisms of information processing and their role in duration perception.

6

General Discussion

6.1 Summary

Perception of the flow of time has been relatively understudied topic. Among the things that makes studying time interesting is how we perceive the present, and how the experience of time flows from the present to the past. Relatively little is known about what the present actually means. William James theorized the present as a unit of duration that has both information from both the past and the future. Another recent proposal by White (White, 2020) describes the present in a similar sense. White theorizes that the perceived present is a very short term construct, and has a duration of ~100 msec. Furthermore, he postulates the present time marker is different from other kinds that describe ordinality (such as order, simultaneity) and duration. Extant literature on the perception of time has documented evidence on perception of ordinal time markers (order and simultaneity) as also operating within the specified ~100 msec. Furthermore, the said ordinal markers of time perception have also been shown to be susceptible to various kind of biases arising from various factors, including but not limited to cognitive biases. This complicates our understanding of what the contents of perceived present are. Therefore, a knowledge of the underlying representations of temporal processing is crucial to solving this puzzle.

In my dissertation, I theorized, investigated and developed novel formal approaches to understand how we represent, experience and remember the perceived present. In Chapter 02, I postulated three different kinds of representations that can be used to study perception of temporal order and simultaneity. The first kind of representation is analogous to a clock, i.e., it uses time to represent time. Note that this kind of representation is perceptual in nature, and could be useful in understanding the contents of the perceived present. The second kind of representation is symbolic, i.e., it is about time, but it does not use time to represent time. An example for this kind of representation would be the numerals used in representing time, i.e., it takes 20 minutes for me to walk a mile. Note that the numeral 20 talks about time, but does not measure every moment in the said duration. The third kind of representation is the one that is not about time, does not use time, but can be consulted to infer temporal properties. An example for this kind of representation is the Reichardt motion detector.

I then reviewed the extant literature on perceived temporal order and simultaneity while keeping an eye on the three representational kinds. While there was evidence pointing towards the existence of temporal representations of the second and third kind, the existence of the first kind of temporal representation has been speculative and a little bit indirect from the existing literature. This is in part due to the hard problem of separating perceptual experience from conception and its associated biases.

In Chapter 03, I investigated what constitutes a moment in visual experience. I did this by developing a novel variant of the Rapid Serial Visual Presentation (RSVP) paradigm that let me probe into the contents of a moment. I found that a moment in our visual experience stitches together events that happened at slightly different times across the visual field. In a series of three experiments, I was able to rule out attention shifts and spatial distance biases as explanations for the observed pattern of results. While this paradigm lets us probe into the contents of our experience, it is unclear whether it provides a complete immunity from conceptual biases as I discussed towards the end of Chapter 01. Further investigation is needed on this front on how to systematically isolate such biases from our perceptual experience.

In Chapter 04, I explored the experience of the elapsed duration. Specifically, I investigated whether we experience time as slowing down in some situations. This phenomenon of slowing down of time is also known as Tachypsychia. The extant literature on the experience of duration has often conflated non-perceptual factors such as attention and memory interacting with the elapsed duration to give rise to the experience of time slowing down. However, note that the amount of time elapsed objectively does not change depending on the situation. A 30 second long car accident still unfolds over 30 seconds no matter how the victims experience it. In order to investigate how our experience of duration elapses, I developed a novel duration judgment paradigm which allowed me to separate the effects of conception from perceptual experience to an extent possible. Accordingly, I found that the atypical stimuli (aka oddballs) were experienced as similar to the standard stimuli. Further, I hypothesized that the distortions of the elapsed duration are a result of how we remember them.

In Chapter 05, I developed three new experiments with potential future directions to test the memory hypothesis. In Experiment 1, I investigated the extent to which memory builds a consistent representation of an event based on its encoding of duration. Specifically, I asked whether the remembered speed is slower than actual when the duration expands. I found that participants reported atypical stimuli as moving slower compared to the standard discs. These atypical stimuli were also reported as expanded in duration. Results from Experiment 1 suggest that our memory builds a consistent representation of events based on encoding of duration. In Experiment 2, I investigated whether oddballs are reported as expanded because of their oddness. Here I manipulated the onset of oddness of oddballs and found that oddness onset is a significant factor in the predicting distortions of the elapsed duration. I further provided an explanation for how oddness onset might affect these distortions using an information accumulation account. This account postulates that the amount of information accumulated during the elapsed duration determines the degree of distortion for the elapsed duration. Further, it also explains why smaller expansion effects were observed for colored oddballs compared to the looming oddballs in the earlier replications of experiments by Tse and colleagues (Tse et al., 2004). I then tested the information accumulation account further by comparing the duration reports when participants judged duration of an empty screen vs. when they judged duration of a screen containing stimuli. I found that participant reports for the duration judgments of an empty screen were longer than the stimulus present condition. This result currently poses a challenge to the information accumulation account as this account predicts the opposite of what I observed. It further highlights the complications such as object specific benefits, distinct mechanisms for judging the duration of emptiness etc., that an information processing account needs to take into consideration, and sets up nice avenues for future work on thoroughly investigating the underlying mechanisms of duration perception and further developing the framework of the information accumulation account.

6.2 Concluding remarks

In conclusion, my dissertation work addresses important questions pertaining to the representation, experience and memory of the perceived time. It emphasizes the necessity to understand the nature of the representations used in processing time to understand the perceived present. It shows that a moment in our visual experience stitches together events from different time points across the space. It further suggests that our experience of the elapsed duration for the oddballs and standards is similar – meaning our perceptual experience of the elapsed duration is relatively stable. However, we might be remembering them as distorted. It opens up potential paths for future research on understanding the mechanisms underlying these distortions.

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Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature*, *453*(7192), 233–235.

Curriculum Vitae

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Education

2016-Present	**Johns Hopkins University, Baltimore, MD**, PhD. Psychological & Brain Sciences
2016-2018	**Johns Hopkins University, Baltimore, MD**, M.A. Psychological & Brain Sciences
2015-2016	**North Carolina State University, Raleigh, NC**, M.S. Electrical & Computer Engineering
2008-2013	**Birla Institute of Technology & Science, Pilani, India**, M.Sc. Physics, B.E.(Hons) Electronics & Communications Engineering

Research Experience

August 2019 – Present
Visiting Student, Tilburg University, Netherlands
Developing computational methods using psycholinguistic theories to understand narrative comprehension in comics
Visual Language Lab | Advisor : Dr. Neil Cohn

August 2016 – Present
Graduate Student, Johns Hopkins University, Baltimore, MD
Developing computational methods, using psychophysics & eye tracking to understand performance limits in visual cognition & perception
Visual Thinking Lab | Advisor : Dr. Jonathan Flombaum

August 2015 – May 2016
Graduate Student, North Carolina State University, Raleigh, NC
Developed computational methods using signal & image processing to remove resipratory artifacts in MRI scans
Advisor : Dr. David S. Lalush

January 2016 – May 2016
Graduate Research Assistant, University of North Carolina , Chapel Hill, NC
Built an EEG processing pipeline & analyzed for frontal asymmetries in the resting state EEG data of patients with Major Depressive Disorder
Advisor : Dr. Flavio Frohlich

August 2014 – December 2014
Research Assistant, Indian Institute of Science , Bengaluru, KA
Programmed & Assisted in building a robotic arm to study motor control of eye-hand coordination in humans
Advisor : Dr. Aditya Murthy

Jan 2013 – July 2014
Research Assistant, Indian Institute of Science , Bengaluru, KA
Developed prototypes & wrote algorithms for an autonomous Indoor Positioning System that can be used for navigating first responders during disaster management
Advisor : Dr. K.V.S. Hari

Teaching

Spring 2020	Instructor - Cognitive Neuroscience, Johns Hopkins University
Fall 2019	Instructor - Research Methods, Johns Hopkins University
Spring 2019	Instructor - Design & Experimental Analysis, Johns Hopkins University
Fall 2018	Teaching Assistant - Sensation & Perception, Johns Hopkins University
Spring 2018	Teaching Assistant - Introduction to Cognitive Psychology, Johns Hopkins University
Fall 2017	Teaching Assistant - Introduction to Psychology, Johns Hopkins University

Publications (Manuscripts in prep & Under review)

2021 **Upadhyayula S.A.**., Ian B. Phillips & Flombaum. J.I. (*In prep*). Space and time dissociate in the construction of a Visual Moment [Watch the talk]

2021 **Upadhyayula S.A.**., Ian B. Phillips & Flombaum. J.I. (*In prep*). Subjective expansion of Time happens in our immediate memory, but not perceptual experience [See the poster]

2021 **Upadhyayula S.A.**., Ian B. Phillips & Flombaum. J.I. (*In prep*). Before, Now & After. A review on temporal properties of perception

2020 **Upadhyayula S.A.**., & Flombaum. J.I. (2020). "A model that adopts human fixations explains individual differences in multiple object tracking." Cognition (2020) : 104418.g [link]

Conferences

2020 **Aditya Upadhyayula**,& Neil Cohn. Hierarchical Structure in Processing Visual Narratives : A computational investigation, talk presented part of symposium at CogSci. 2020

2020 **Aditya Upadhyayula**, Ian Phillips & Flombaum. J.I. Space and Time Dissociate in the construction of the Visual Now, talk presented at V-VSS 2020

2020 Ian Phillips, **Aditya Upadhyayula** & Flombaum. J.I. Tachyspychia - subjective expansion of time - happens in immediate memory, and not in perceptual experience, poster presented at V-VSS 2020

2019 **Upadhyayula, Shanmukha**, and Jonathan Flombaum, "Distortions of time perception", presented at Mid Atlantic Memory and Attention conference

2019 **Upadhyayula, Shanmukha**, and Jonathan Flombaum, Two distortions of perceived space and time, presented at Object Perception Attention & Memory (OPAM)

2019 **Upadhyayula, Shanmukha**, and Jonathan Flombaum, The Visual Now across the visual field, presented at Captial Area Cognition Action & Perception

2018 **Upadhyayula, Shanmukha**, and Jonathan Flombaum, "Object size affects multiple object tracking performance (but not via frequency of close encounters)." Journal of Vision 18.10 (2018) : 1020-1020.

Selected Invited Talks

2021 University of Giessen, Germany - Joint lab meeting between Gegenfurtner & Scene Grammar Labs (PIs : Karl Gegenfurtner & Melissa Vö)

2021 Yale University, CT - Cognitive & Neural Computation Lab (PI : Ilker Yildirim)

2021 University of California Davis, CA - Visual Cognition Group (PI : John Henderson)

2021 New York University - Ma Lab (PI : Weiji Ma)

2020 Tilburg University, Netherlands - Groningen-Tilburg joint workshop on Pictorial narrative comprehension

2020 University of California, San Diego, CA - Cognitive tools lab (PI : Judith Fan)

2019 Villanova University, PA - Mid Atlantic meeting on Memory & Action

2018 Georgetown University, DC - Captiol Area conference on Cognition, Action & Perception

2018 Johns Hopkins University - Seminar on Computational Psycholinguistics (PI : Tal Linzen)

2018 Johns Hopkins University - Dynamic Perception Group (PI : Jason Fischer)

2017 Johns Hopkins University - Computational Cognition, Vision & Learning group (PI : Alan Yuille)

2017 Johns Hopkins University - Honey Lab (PI : Chris Honey)

Skills

Programming	**Python MATLAB**, **R**, **C**, **Eye Tracking**, EEG processing, Javascript, HTML, Java
Operating Systems	MacOs, Linux, Windows
Software	**PyTorch**, **Psychopy**, **Psychtoolbox**, **Plotly**, Tensorflow, Eyelink 1000 plus, EEGLAB

Honors and Awards

2021 G. Stanley Hall Scholar Award - Awarded to a student who has demonstrated exceptional scholarly progress in dissertation research ($500)

2019 Travel Award, Object Perception Attention and Memory conference ($250)

2019 Departmental Collaborative Research Grant Award | Topic : Individual differences in temporal integration of music | Jointly recieved with Hsiang-Yun (Sherry) Chein ($1000)

2016 - present Robert S. Waldrop Graduate Student Fellowship

References

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